Understanding How Humans Re-learn to Walk with a Simulated Unilateral Prosthesis

Honors Undergraduate Research Thesis

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Abstract

Walking patterns may change due to external reasons such as injuries, disease, and more. Understanding such changes would inform approaches to rehabilitation after such injury or disease. In some situations, such as after an amputation, humans may need to re-learn how to walk with the new prosthetic device. To address these issues, it is important to understand how humans learn to walk and how human walking changes under different conditions. Humans learn to walk at a young age, often at around the age of one year old, and continue to develop their walking patterns until they mature. It is difficult to study these walking patterns due to the young age that walking is leaned by humans.

In this study, we recreate the learning process of walking for a short period of time by studying how non-amputee humans wearing the iWALK 2.0 unilateral prosthesis relearn to walk in attempt to characterize ground reaction force magnitudes and body motion variability to evaluate performance and potential improvement. We collected data from ten subjects, after informed consent and International Review Board (IRB) approval. Each subject was equipped with light reflective markers on the abdomen, both the left and right foot, shank and hip. The markers were used to track movements with a Vicon motion capture system. Subjects walked on a treadmill with a left and right force plate to measure the ground reaction forces and torques during each trial. Data was collected from each subject walking without the iWALK 2.0 for roughly three minutes and with the device attached to the right leg for roughly 20 minutes.

Results showed, all subjects displayed a symmetric walking pattern in terms of the vertical ground reaction force while not wearing the device. While using the device, all subjects placed more average force on their left leg (leg without the device), while unloading the right leg (with the device). While wearing the device, the free leg endured an average of 60% of the weight. Three

out of ten subjects showed a significant increase in symmetry, balance of forces between right and left leg, throughout their time walking with the device, but every subject, other than subject 3, had a higher force symmetry at the end compared to the initial minute of the walking trial. When walking with the device, average stance phases were longer on the left side than the right for all such trials, for all subjects. During the experiment, we collected much more data than could be analyzed within this thesis.

The results of this study and further analysis of the data may provide insight into what trends exist in the mechanics and control of walking as these subjects to learn how to re-walk. With a better understanding of how humans learn to walk, improvements can potential be made to assistive walking devices and physical training techniques with the knowledge of humans' initial approach to a new limb and how they progress over time in a new walking situation. This research also may potentially be used to aid the development of human-like robotics by using walking data to help provide better controller response in robotics, allowing for more "life-like" robotics.

Acknowledgements

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Chapter 1 : Introduction

1.1 Background and Motivation

Walking is one of the most performed movement activities among humans. Despite the frequency with which walking is performed, it is a “very complex action” using “almost all of the muscles of the human body” (Watelain, 2017). Learning to walk, either learning to walk at the beginning of one’s life or for re-learning after injury, is a complex process. Walking patterns can be compromised due to injury, disease, or even amputation. Due to the complexity of walking, re-learning walking patterns after substantial such injury or disability is difficult and sometimes impossible. Understanding how humans learn to walk would inform approaches for rehabilitation after injury or disease, which may allow for better and faster rehabilitation. To aid in this understanding, it is important to know how humans learn to walk and how their walking changes under different conditions. Historically, it has been harder to study humans when they learn to walk because it is done at a very young age (Watelain, 2017). In this study, we look to create a re-learning the process of walking, in a short period of time, by studying non-amputee humans (without injury) walking with the iWALK 2.0 (figure 1.1) simulated unilateral prosthesis for the first time. Studying subjects walking with the iWALK 2.0, a hand free crutch, allows us to evaluate their performance, their possible improvement, and their ability to learn with the device through quantification of reaction forces and observation of body motion variability.

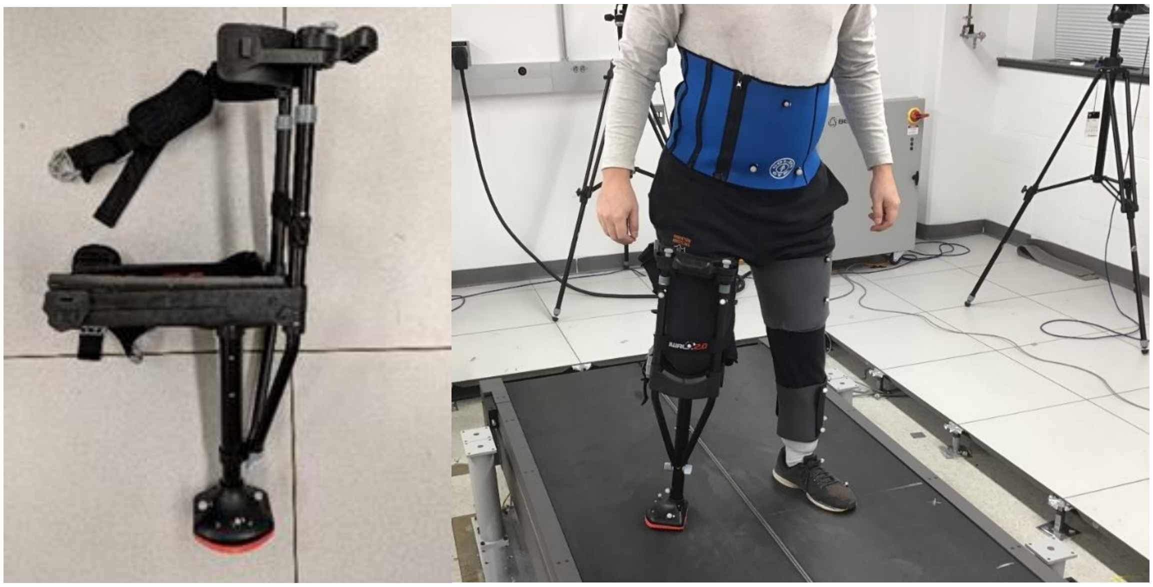

Figure 1.1: iWALK 2.0 unilateral prosthesis used to simulate the learning phase of walking for subjects wearing this device for the first time. Each subject walks while wearing the iWALK 2.0 for roughly 23 minutes total across all trials (to be described in the methodology section). Right image from Shepherd, 2018.

1.2 Objective

Specifically, the overall objective is to characterize learning in human subjects walking with a simulated unilateral prosthesis for the first time in order to: determine and characterize each subject's ground reaction force magnitudes, walking symmetry, and body motion variability during learning; and then evaluate subjects for improvement (e.g., is walking becoming more symmetric, less effortful, more stable, etc.).

1.3 Literature and Significance

"Gait" is a term that refers to the usual pattern on movement during locomotion. This usual movement pattern is sometimes affected, often due to a physical or neurological condition. Assistive walking devices are often used to improve and/or correct changes in gait.

We now discuss a few research articles that have studied the use of assistive devices (from among thousands of such articles) or sensors to track human walking through learning or adaptation. Mekki et al (2017) discuss the use of assistive devices for different injury and disease cases. They discuss the benefits of different devices such as walking sticks, canes, crutches and walkers, but focus on a modified cane that is personalized and monitored to test Parkinson patients (Mekki, et al, 2017). The study provides a way of analyzing walking in Parkinson patients and tracking their long term gait changes, whereas in our study, we are finding a way to analyze able body (healthy) patients in a condition that allows them to relearn the walking phase. As noted, such understanding of learning or adaptation could be used to help with quicker rehabilitation for those that have a path to returning to their preinjury gait.

Exoskeletons are assistive devices used for rehabilitation to enhance mobility. Chen et al (2017) performed a study on step length adaptation while using exoskeletons to understand and improve the adaptation of the exoskeletons to the motions of the person. Their results showed that the proposed step length adaptation method used by the exoskeleton was able to adapt to the motion changes by the subject (Chen et al, 2017). Advanced assistive walking devices, such as exoskeletons do have the ability to adapt with the user, but may be improved with optimization. Zhang et al (2017) developed successful methods to decrease energy cost when using an exoskeleton during walking. They discuss how optimizing characteristics of the exoskeletons, based on human performance, can lead to an improved design and improved performance (Zhang et al, 2017). In contrast to these studies of exoskeleton adaptation or adaptation to wearing an exoskeleton, our study will examine how individuals learn to walk with an adverse condition in a short time-scale. Such information could be used to adjust assistive devices, such as an exoskeleton, to specifically fit the patient based on data collected. Our study could potentially lead to a better understanding of human walking patterns. With this information, optimization methods could be developed to improve performance of assistive devices, such as the exoskeleton.

When subjects are walking with the iWALK 2.0, we expect there to be improvement by the end of the trial for most, if not all participants. One way to measure improvement in walking is to quantify the stability of the subject. Srinivasan and co-workers have conducted multiple studies understand and/or measure stability, especially showing how foot placement is critically used in stabilizing walking and running dynamics. In a study by Perry and Srinivasan (2018), foot placement response is monitored with change in average step width (5 widths tested) and upper body motion variation. This study found that the change in step width does affect the foot placement, but stability was not significantly affected by the changes in step width or upper body motion (Perry and Srinivasan, 2018). A study by Seethapathi and Srinivasan (2019) examines step-to-step variation during running. In this study, they were able to find considerable information regarding running strategies with variable conditions. This study found that the center of mass is a good predictor for foot placement. It was found that humans use foot placement to direct the leg force to oppose perturbation (Seethapathi and Srinivasan, 2019). These studies show that most humans have a natural ability to stabilize themselves in some adverse conditions. In our study, we hope to eventually evaluate how well our subjects can stabilize their walking in a situation they have never been in before, walking with the iWALK 2.0. Evaluating ground reaction forces, we can see the difference in weight distribution on the left (free leg) and right (device equipped leg) throughout the trial. This will provide us with a measure of improvement known as stability. If the subjects become more stable throughout the short trial, it can be assumed that they have improved their walking technique with the device.

Most humans learn and begin to develop their walking techniques as children. Testing in children may be the most ideal situation to understand how humans learn to walk. Unfortunately, it is more difficult to test and study children with as great an accuracy as adults, at least at the age they begin walking (around one year of age). Woollacott et al (1998) did a study on the development of balance control in children standing. In this study they "show a clear developmental progression of the emergence of organized muscle response patterns, with tonic background muscle activity decreasing and phasic bursts of activity emerging in all three agonist muscles in a synergic group (gastrocnemius–hamstrings–trunk extensors or tibialis anterior–quadriceps–abdominals) just prior to the onset of independent stance." (Woollacott et al, 1998). They tested healthy children in conditions to mimic children with cerebral palsy (CP). Under these conditions, they found similar results in healthy children as to the CP children, suggesting that balance control is affected by both biomechanical changes in postural alignment and the central nervous system (CNS) (Woollacott et al, 1998). Assaiante et al (2005) studied young subjects with adaptation of postural strategies aimed at testing short and long-term adaptation capacity of the CNS during imposed transient external biomechanical constraints in healthy children. They found that the first reference frame used for balance control during locomotion is the pelvis (especially in young children), whereas head stabilization was found to take much more time to develop during locomotion. They determined for balance in children, the first step is to develop postural strategies and the second is to select the best fit posture for the circumstance (Assaiante et al, 2005). These studies show that, when children learn to walk and stand, balance strategies and learning how to use those strategies are very significant for development. In our study, we re-create a learning process of walking. In this study, we hope to see what strategies are attempted and most favorable in the early stages of learning to walk.

Humans stand before they can walk. Standing still already requires a mastery of balance that is essential to walking, especially slow walking. A previous study (undergraduate thesis) by Robert Shepherd at the Movement Lab at Ohio State examined humans learning to stand with same device (iWALK 2.0). In his study, subjects were to wear the device for the first time and stand with the device for 30 minutes. Robert found that over time, subjects became more stable, shifting weight from the non-prosthesis leg to the prosthesis leg, approaching similar standard deviations in various quantities that they would have without the device (Shepherd, 2019). Roberts' study showed success in the subject's ability to stabilize while standing with the iWALK 2.0. In our study, we will have subjects walk with the iWALK 2.0 to evaluate how the subjects approach a new walking situation and potentially improve and become more stable using the device. This will allow us to see able body walkers learning to re-walk in an adverse situation. This study provides us with the potential to learn more about how the body learns to walk. This knowledge may be significant for improving rehabilitation (both therapy techniques and assistive devices). A potential extended application of this study is to improve human like robotics. With knowledge of how humans learn to walk, robotics can be improved, adjusting the control system responses to respond more like an able body human.

We refer to the iWalk 2.0 as a "simulated prosthesis" in this thesis because it functionally replaces the knee downward with itself, so that the subjects' ankle torques and knee torques (ideally) play little to no role during walking. Of course, there are significant differences between this and an amputee wearing a typical above-knee prosthesis: for instance, the inertia, sense organs, and the musculature of the biological limb attached to the iWalk device which may still play a small role during walking.

In this thesis, we focus on symmetry between the function of the two legs during walking. Note that there is a large literature on symmetry in unilateral amputees walking with a prosthesis, both powered and passive prosthesis; we refer the reader to Handford and Srinivasan (2019) and Seethapathi and Srinivasan (2020) for a brief review of such literature and related results. A future article will make explicit comparisons between our results here and such past work on amputee symmetry.

1.4 Thesis Overview and Research Goals

The goal of the research presented in this thesis is to study subjects walking with a simulated unilateral prosthesis for the first time to understand how they re-learn to walk and how that walking changes. This thesis consists of 5 chapters: Introduction, Methodology, Results, Discussion, and Future Work and Conclusion. Chapter 2 discusses the methods conducted to collect and analyze data, including: subject population, equipment used, experimental procedure, and programing tools. Chapter 3 discusses the results of the data collection and analysis. Chapter 4 explains significant details of the results, their implications, and the limitations of the study, including discussion of other planned analyses that were not conducted due to time-limitations. Chapter 5 summarizes our primary conclusions and points to various potential future work and analyses.

Chapter 2 : Methodology

Before beginning experiments and data collection, approval was gained from The Ohio State University International Review Board (IRB) to ensure everyone working on this research was well informed and certified to work with human subjects. The experimental protocol, described below, involving subjects walking with and without a simulated unilateral prosthesis (iWalk 2.0) was approved by the IRB.

2.1 Subject Recruitment

Ten subjects (N = 10) participated in this study. Subjects were recruited for this experiment through email advertisements sent to the Mechanical and Aerospace Engineering (MAE) student body. Participation in this study was limited to those who: were healthy and between the ages of 18-60; can stand, walk, and run at moderate speeds independently, and have no known movement disorders; have no history of heart or lung problems; and are not pregnant. All participants provided informed consent and were provided payment as stated in the IRB protocol.

2.2 Subject Population

Of the 10 subjects, 5 were male and 5 were female. Subject heights ranged from 158.8 centimeters to 191.8 centimeters (full) and 76.2 centimeters to 96.5 centimeters (hip). The weight of the subjects ranged from 555.4 Newtons to 1112.5 Newtons. The table below summarizes the subject measurements and identification.

Subject Number	Weight (scale) [N]	Height (full) [cm]	Height (hip) [cm]	Subject Age	Male or Female
1	1112.5	185.4	96.5	22	M
2	825.0	180.3	91.4	21	M
3	683.5	177.8	91.4	21	M
4	620.3	180.3	87.6	21	M
5	643.0	181.6	91.4	20	F
6	615.9	158.8	81.3	23	F
7	573.2	168.9	86.4	19	F
8	939.0	191.8	94.0	21	M
9	555.4	168.9	76.2	19	F
10	851.7	182.9	91.4	20	F
Average	741.9	177.7	88.8		
Maximum	1112.5	191.8	96.5		
Minimum	555.4	158.8	76.2		
Standard Deviation	183.2610219	9.587355156	6.118594701		

Table 2.1: Anthropometric measurements (height: full and hip, and weight) for all subjects with calculate mean, maximum, minimum and standard deviation as well as age and sex of all subjects.

2.3 Equipment

The movement lab at OSU was used to conduct the experiments. Light reflective markers (Figure 2.1) were attached to the subjects on the abdomen, both hips, both shanks, and both feet.

Figure 2.1: Reflective motion capture markers placed on subjects, used to provide motion feedback to the Vicon system. Markers reflect the LED light produced by the cameras to send feedback to the system. This feedback is the motion of the markers based on the relative location.

The light reflective markers were used to track the position of each subject through motion capture with the Vicon cameras. Motion data captured by the cameras would be saved to the Vicon Nexus software on the workstation. Subjects walked on a two-sided treadmill equipped with a force plate under each side. The Vicon motion camera set up and the force plated treadmill can be seen in figure 2.2. This treadmill can be controlled at the same workstation that the data collection occurs. The force plates can measure the reaction forces in the x, y, and z direction along with the reaction torque and the center of pressure (COP).

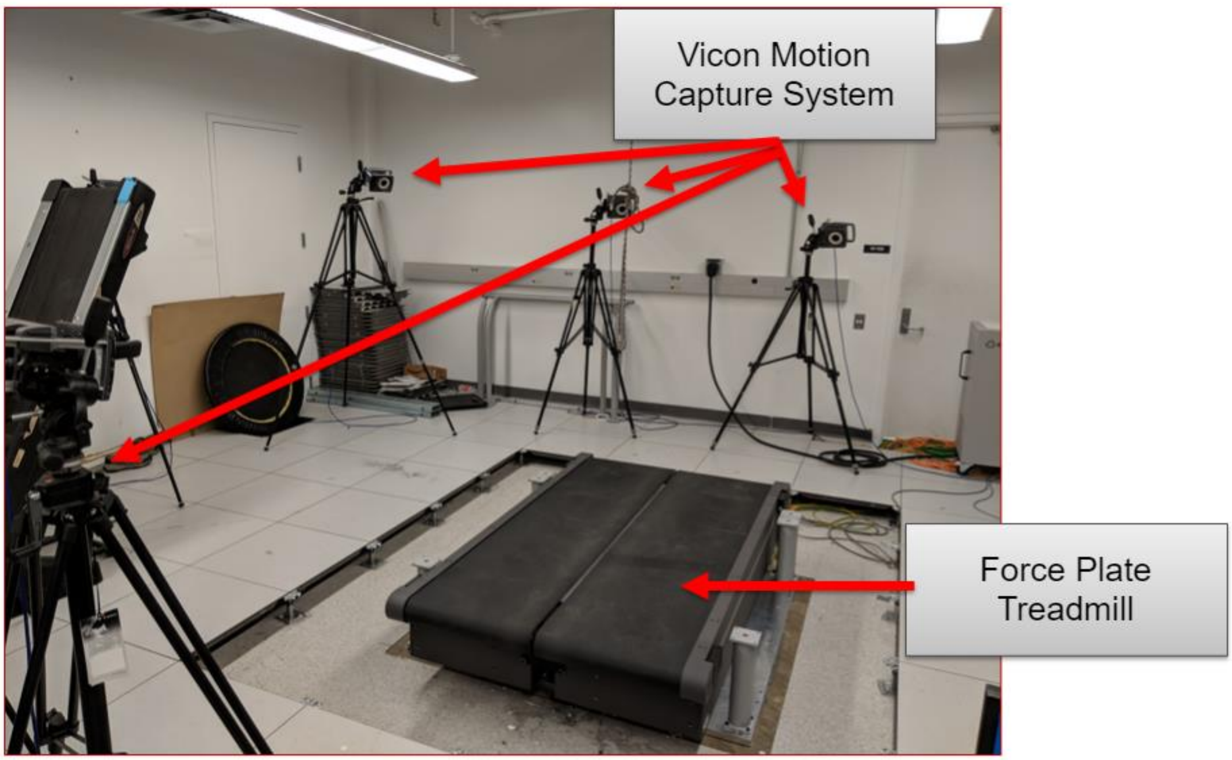

Figure 2.2: Movement lab set-up including the dual force plated treadmill for force evaluation, and the Vicon motion capture cameras. Treadmill has a force plate on each half to measure forces in the x, y and z direction, torques and the COP.

To simulate a new walking condition, subjects walked with the iWALK 2.0 (Figure 2.3). The iWALK 2.0 is an unassisted walking crunch that allows users to walk with either one hand or both hands free.

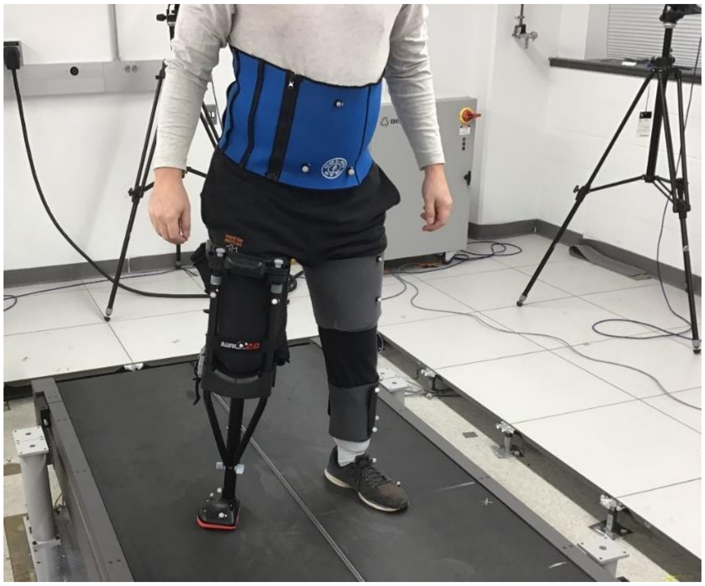

Figure 2.3: iWALK 2.0, unilateral prosthesis, used as a hands free crutch to simulate learning how to walk. Device and motion capture markers shown being properly worn in the second picture. Photograph from Shepherd, 2019.

Lastly, a loose harness tied to the concrete ceiling is used for subject safety while walking with the device. Data was recorded and stored with the Vicon capture software and was analyzed using Matlab.

2.4 Experimental Procedure

We prepare the lab by starting up the Vicon system (software and hardware) and the force plated treadmill. For each subject, a separate subject file was created to store all motion and force data for the various trials performed with the subject. The Vicon cameras are calibrated using a manufacture provided "5-point calibration wand" (Figure 2.4). The calibration process determines the camera location and orientations by using a few seconds of recordings of the calibration wand. The wand has five markers at known relative locations, after each camera reads the wand the correct number of times, the cameras are able to determine their own location relative to the wand. After this is completed, the wand is placed at the center of the treadmill where the origin location is set.

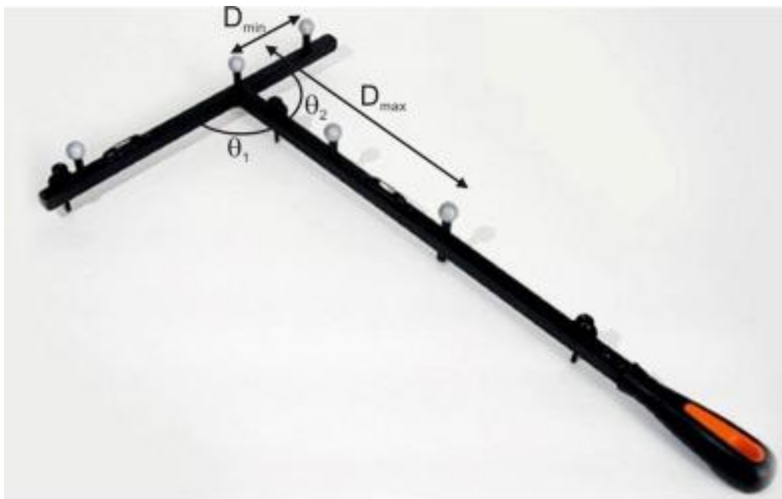

Figure 2.4: Vicon motion 5-point calibration wand used to calibrate the cameras by establishing a relative position based on the systems knowledge of the wand marker configuration. The wand is also used to set the origin of the system. Image from: https://www.sciencedirect.com/science/article/pii/S0263224116000099

After calibration, the system is ready for operation. Before beginning, the subjects were presented with and asked to read and sign the IRB approved consent form (if they chose to provide informed consent) along with being briefed on the experiment. After consent has been provided, the subject is to put on the safety harness which is be inspected by the operator. The subject is then fit with the light reflective markers on the abdomen, hips, shanks and feet. Next, anthropometric measurements are taken of the subject. The subjects' heights (total and hip) are measured with a tape measure and the subjects' weight is measured with a bathroom scale. For additional weight characterization, the subject then stands on the two belts of the treadmill, for 5 seconds each, to compare each force plate reading to the scale.

The next step was to collect the subjects' walking data without the device. For this trial, trial 2, the subject walked with one foot on each side of the treadmill. This treadmill is accelerated ($a_1 = 0.05\frac{m}{s^2}$) from rest to full speed ($V_2 = 0.6\frac{m}{s}$) for roughly 3 minutes. Next the subject is fit with the iWALK 2.0 device. Fitting instructions from the manufacturer's website were followed to ensure the device was attached proper. The fitting of the device is important to insure the subject's condition and the fit do not change during the experiment. For a proper fit, straps needed to be tight, not allowing the device to sway. Due to the strap design, the device could become lose and need adjusted. Readjustment occurred in eight of the ten trials. After the subject is properly fit with the device, the subject was asked to move around the treadmill slightly to evaluate the fitting. Adjustments were made until the participant feels the device is fit properly and comfortable. The subject was instructed to use the device's support handle as much as they wanted but to only use the support bars on the treadmill if necessary, for short periods of time. The subjects were told to alert us at any point if the device became loose enough to affect their walking ability. After instructions were given, the subject then began walking on the treadmill with the device, this was trial 3. The subjected was accelerated ($a_2 = 0.01\frac{m}{s^2}$) to half speed ($V_1 = 0.3\frac{m}{s}$) where the subject will walk for roughly 3 minutes. After roughly 3 minutes, the subject was asked if they were ready to increase speed. Velocity was then accelerated ($a_2 = 0.01\frac{m}{s^2}$) from half to full speed (0.6 m/s). The subject then walked with the device at full speed for roughly 20 minutes. Periodically during the trial, the subject was asked if the device was still fit properly. In 8 out of 10 cases the subjects needed to stop the walking trial at least once for adjustments to the device. The 8 subjects that needed to stop trial 3 for a break and/or device adjustment performed one or two more trials (labeled trials 4, 5, and so on) until the 20 minutes of walking with the device was completed. After completion of the trials, the subjects were helped out of the equipment.

2.5 Data Analysis

Motion capture and ground reaction force data was analyzed in MATLAB. Motion capture data can be used to visually identify step patterns and body posture during the experiment and how it changes throughout time. The motion data provide visual indication as to what the subjects are doing to try and learn how to use the device. The force data are used to evaluate the symmetry of and changes in the vertical ground reaction forces. The ground reaction forces were plotted over entire trials as well as small portions of the trials. The small intervals provide the data of potentially each stance phase.

To quantify the left-right symmetry of various quantities, we computed an index of symmetry: for instance, for average leg force borne by each leg, we computed the following index of symmetry, equal to the average right leg force divided by the average total leg force (all in the vertical direction):

Index of symmetry = average right leg force / average total leg force.

The gait is symmetric in this metric when this index is equal to 0.5, biased toward the left leg when this index is less than 0.5, and biased toward the right leg when greater than 0.5. We compute such symmetry indices for other mechanical quantities as well, all using the ground reaction force measurements. Note that symmetry in one such index still allows the gait to be left-right asymmetric along other quantities.

We focus on symmetry in this study because symmetric walking (or close to it) is what most humans typically perform in the absence of body or environmental asymmetries. Indeed, all subjects in this study performed close to symmetric walking when walking without the device. It is considered to be biomechanically good to walk symmetrically, an equal force distribution on both legs, for efficiency, and avoidance of comorbidities like osteoarthritis.

Chapter 3 : Results

All subjects performed at least 3 trials. Trial 1 was a standing trial, without wearing the device, to measure body weight on the treadmill. Trial 2 was a walking trial of the subject without wearing the device. Trial 3 was a walking trial of the subject while wearing the device. Some subjects performed more trials if their trial 3 got interrupted.

3.1 Asymmetry in Vertical (Z) Ground Reaction Forces

We found that all subjects were substantially asymmetric during walking with the device. All subjects walked such that more force was transmitted through the leg that was "free" (the device was not attached to that leg). Table 3.1 below shows the average total (left + right) force recorded over all trials, the average force on the left treadmill during all trials with the device, and the average force on the right treadmill during all trials with the device for subjects 1-9 (force data for subject 10 could not be processed due to a software issue).

Average Forces For all Subjects [N] while wearing the device			
Subject	Average Total Force (Body Weight)	Average Left Force (Device Trials)	Average Right Force (Device Trials)
1	1147.6	684.2	464.3
2	791.5	470.4	309.3
3	717.0	407.3	312.1
4	672.4	400.4	275.9
5	711.7	430.9	285.9
6	656.9	396.8	263.4
7	633.2	385.5	252.6
8	978.1	621.3	360.4
9	592.4	381.0	214.4
Average	766.7555556	464.2	304.2555556
Standard Deviation	182.0151581	111.352189	72.80613146

Table 3.1**:** Average force in the vertical (Z) direction while wearing the device. The total force is an average of both the left and right forces for each subject for all trials. The average left force is an average of all forces on the left side of the treadmill for all trials while wearing the device for each subject (the side where the subject is walking without the device). The average right force is an average of all forces on the right side of the treadmill for all trials while wearing the device for each subject (the side where the subject is walking with the device).

We compared the asymmetry for the walking trial where the subjects do not wear the device with the asymmetry for all walking trials where the subjects wear the device. Table 3.2 below lists an index of symmetry, where 0.5 is symmetric, defined as the right force divided by the total force for each subject. Note that the subjects wore the device on the right leg, so this index of asymmetry is the "normalized device leg force" (device leg force divided by total force) for the trials with the device. In all cases, as expected, the subjects focus less force on their right leg during trials in which they wear the prosthesis than the trial in which they do not wear the prosthesis. Figure 3.1 below displays the data presented in table 3.2.

Subject Symmetry (Right leg Force over Total Force)			
Subject	Trial without Device	All Trials with Device	Difference
1	0.4957	0.4043	0.0914
2	0.4904	0.3967	0.0937
3	0.4952	0.4338	0.0614
4	0.4922	0.4079	0.0843
5	0.4917	0.3989	0.0928
6	0.4987	0.399	0.0997
7	0.5046	0.3959	0.1087
8	0.4955	0.3671	0.1284
9	0.5014	0.3601	0.1413
Average	0.496155556	0.395966667	0.100188889
Standard Deviation	0.004683244	0.021740688	0.023689789

Table 3.2: The index of symmetry, the average of the right vertical force divided by the average of the total force (summation of right and left vertical forces): shown for the one trial not wearing the device and for all the trials wearing the device.

Subject 4 had the maximum normalized device load of 0.4079, so closest to symmetry by this metric. Subject 9 had the minimum normalized device load of 0.3601, so used the non-device side the most and the device side the least

The standard deviation in this symmetry index for trials walking while wearing the device was 0.0217. Subject 3 had the least change in force symmetry (smallest difference in symmetry between trials with and without the device) with a difference of 0.0614 and subject 9 had the greatest change in force symmetry of 0.1413. On the normalized right leg force without the device was greater than while wearing the device (over the 9 subjects) by 0.1002 with a standard deviation of 0.0237.

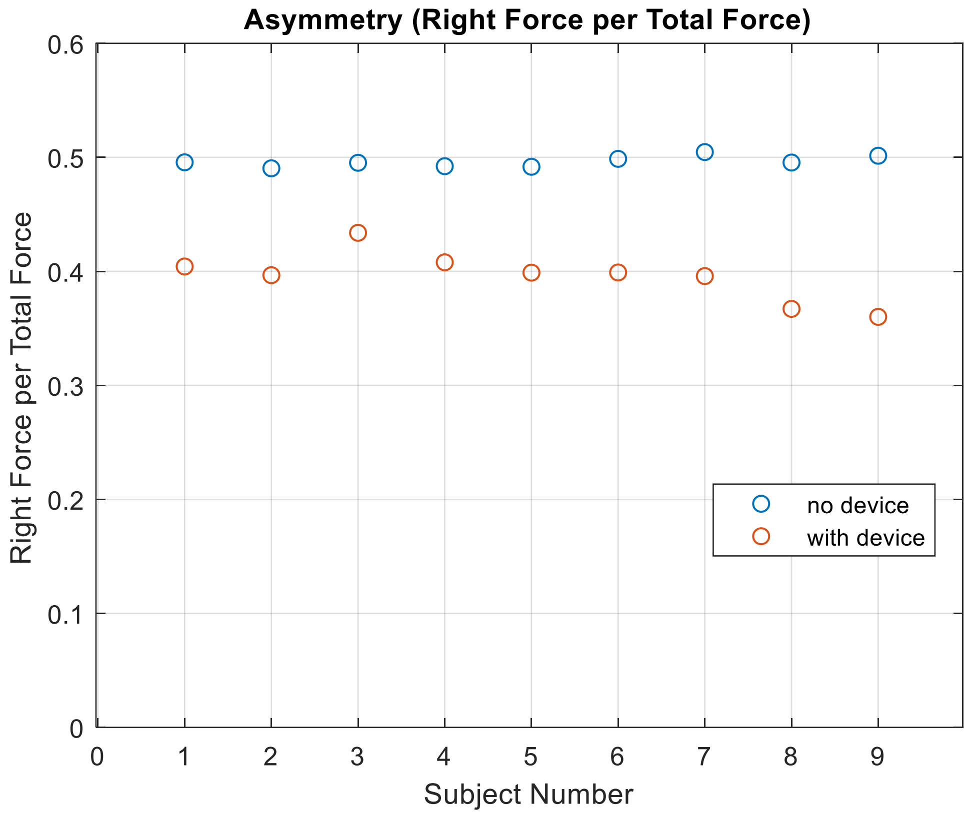

Figure 3.1: Symmetry index (average of the right force divided by the average of the total force) for the trial of the subject walking without wearing the device (blue) and all trials of the subject walking with the device for all subjects 1-9 (orange). For walking trials while wearing the device, the right leg is attached with the device and the left leg is free.

3.2 Asymmetry in Stance Durations

Stance phase of a leg is usually defined as when the leg is in contact with the ground. Here, the stance phase, for each foot, is defined as the time the subject has that foot placed on the treadmill, enough to result in a vertical force of at least 100 N, a threshold sufficiently above the noise floor. To remove noise and potential time when subjects were in stance on both the left and right side of the treadmill, stance phases that were lower than 200 ms or were different from the median by 40% were removed. Table 3.3 below shows the average stance time, of both the left and right foot, for each subject separated by each trial performed.

Time in milliseconds	trial 2 (no device)		trial 3 (with device)		trial 4 (with device)		trial 5 (with device)	
Subject	Left	Right	Left	Right	Left	Right	Left	Right
1	1037	1043	967	786	953	754		
2	919	888	1019	776				
3	803	773	824	677	788	646		
4	781	760	1072	730	830	636		
5	930	900	1253	676	1321	665	986	686
6	820	813	947	619	812	579		
7	850	843	961	604	883	615		
8	1058	1034	1160	786				
9	884	908	909	552	958	581		

Table 3.3: Average time (in milliseconds) of each stance on the left and right side of the treadmill for all walking trials (with and without the device) for subjects 1-9. Trial 2 is the walking trial without wearing the device, trials 3 and on are the walking trials while wearing the device.

For each stance phase, the average force from the left and the right treadmill was determined. The mean forces were calculated for each subject during each walking trial. Also, for each stance, the maximum force on each side was determined. The maximum force allows us to see the peak of each stance, which allows for additional comparison between the free and prosthetic leg. Each subject performed at least two trials (walking without the device and walking with the device), eight out of ten subjects performed at least one additional trial walking with the device (needing to stop for rest and/or to adjust the device fitting). Figure 3.2, 3.3 below and 6.1 (appendix) show the average and maximum force per stance phase for subject 1 (all trials). The average and maximum force per stance phase for subjects 2-9 can be found in the appendix, figures 6.2-6.24.

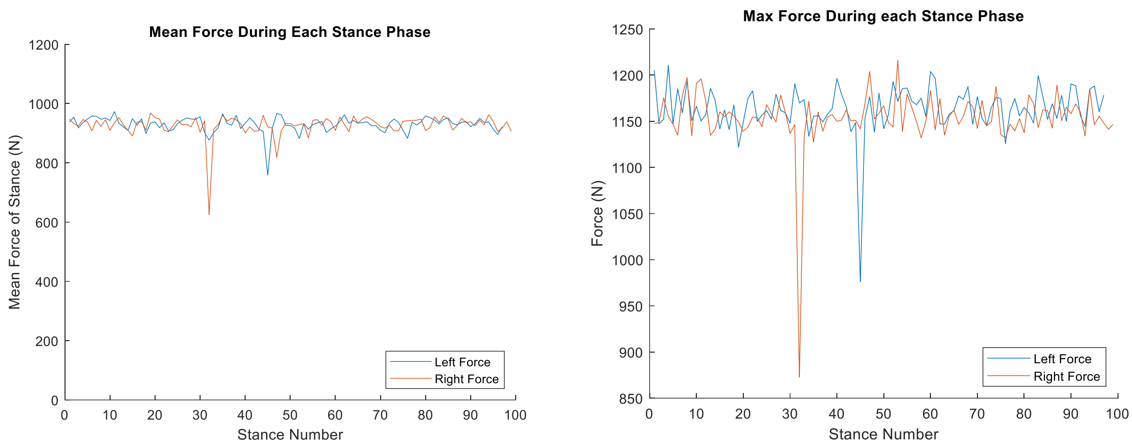

Figure 3.2: Left plot: Mean left and right force during each stance phase for subject 1, for the trial walking while not wearing the device. The average forces are roughly equal, denoting near symmetry. Right plot: Maximum left and right force during each stance for the discussed trial. Shift in higher left and right peaks can be seen

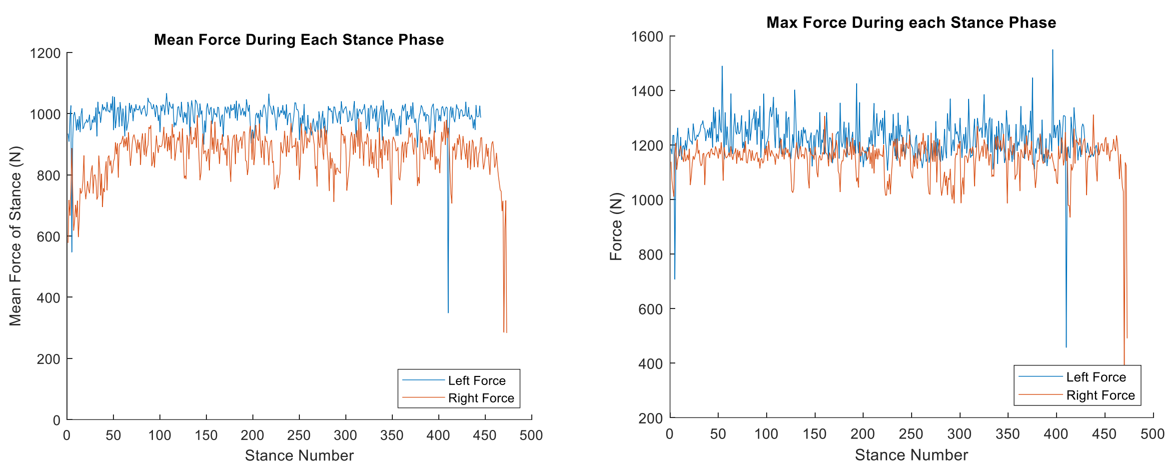

Figure 3.3: Mean left and right force during each stance phase for subject 1, for the first trial walking while wearing the device. The average right leg forces are substantially lower, reflecting the asymmetry described earlier. Maximum left and right force during each stance for the discussed trial.

Thus, we find that the substantially lower force on the device leg is mainly due to much lower stance phase duration for that leg (Table 3.3), rather than much lower forces during the stance phase itself (Figures 3.2-3.3). That is, the device leg contributes less average force by spending much less time exerting forces (and only slightly lower forces when it does exert a force).

3.3 More Detailed Visualization of the Vertical Forces

In the rest of this section, we visualize the vertical ground reaction forces (thresholded by 100 N) and normalizing by the person's body weight. Figure 3.4 below shows the left and right forces during all trials for subject 1 while wearing the device, plots for subjects 2-9 can be found in the appendix (figures 6.25-6.32). The dot-dash line represents the time when the speed is increased from V_1 to V_2. The dashed lines represent when a trial ended. In eight out of ten cases, the subject performed more than one trial walking with the device as explained in the experimental procedure.

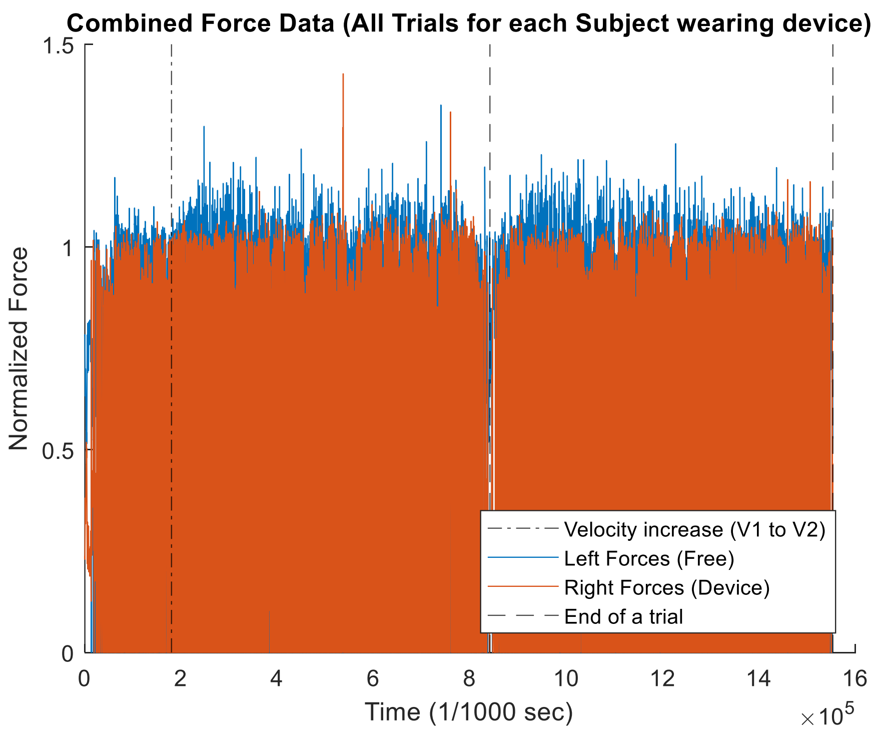

Figure 3.4: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 1, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

Visualizing the whole trial as in Figure 3.4 does not allow us to discern the intra-step trends over the twenty-minute trials. So, for clarity, data for 30 second intervals were plotted for each subject. The top of figures 3.5-3.13 show normalized force of subjects 1-9 walking without the device (minute 1 through minute 2). This data was collected and plotted to show how the subjects walk without the device. The bottom of figures 3.5-3.13 show subplots of normalized force of each subject walking with the device. The subplots are divided up into 30 second intervals at the 5-5:30 minute mark, the 10-10:30 minute mark, the 15-15:30 minute, and the first 30 seconds of the final minute. This allows the subjects vertical reaction forces when walking with the device to be analyzed at the beginning, middle and end of the experiment. We see that in these visualizations, the maximum forces on the left and right legs are not as different as the average forces on the left and right treadmill, suggesting that the average right leg forces are lower primarily due to lower time spent on each leg.

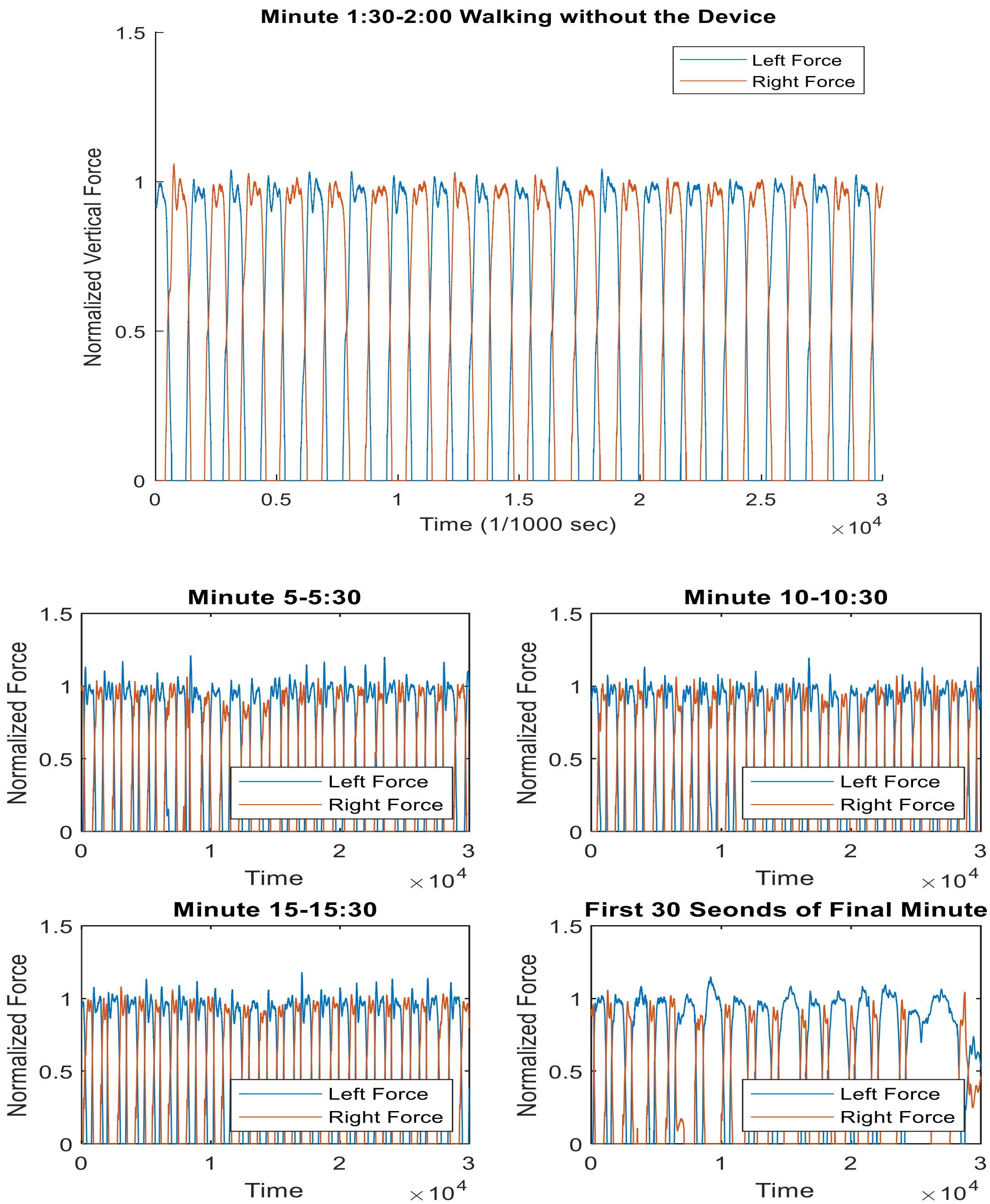

Figure 3.5: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 1, during the walking trial without the device during the 30 second time from of 1:30-2:00. Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

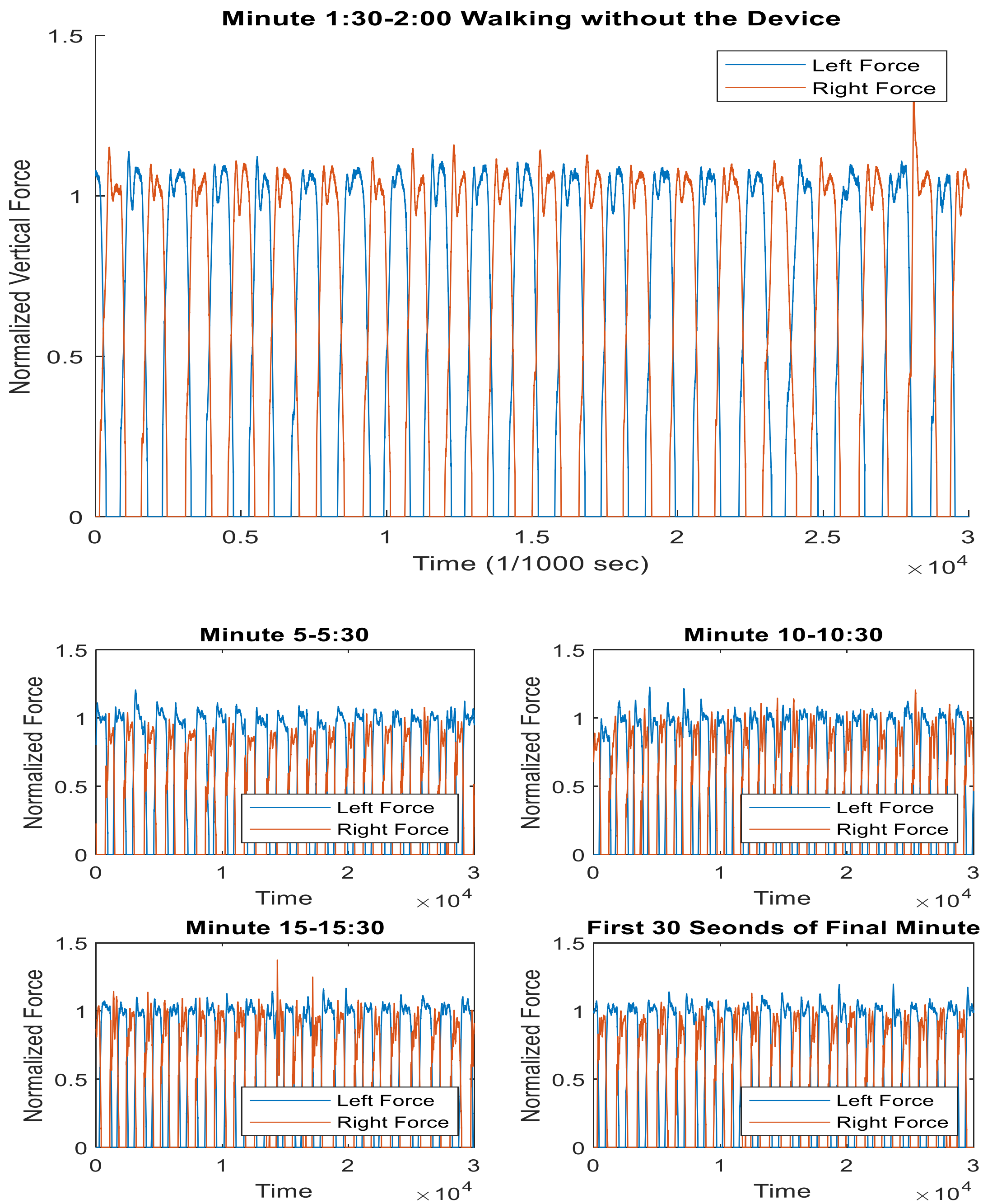

Figure 3.6: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 2, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

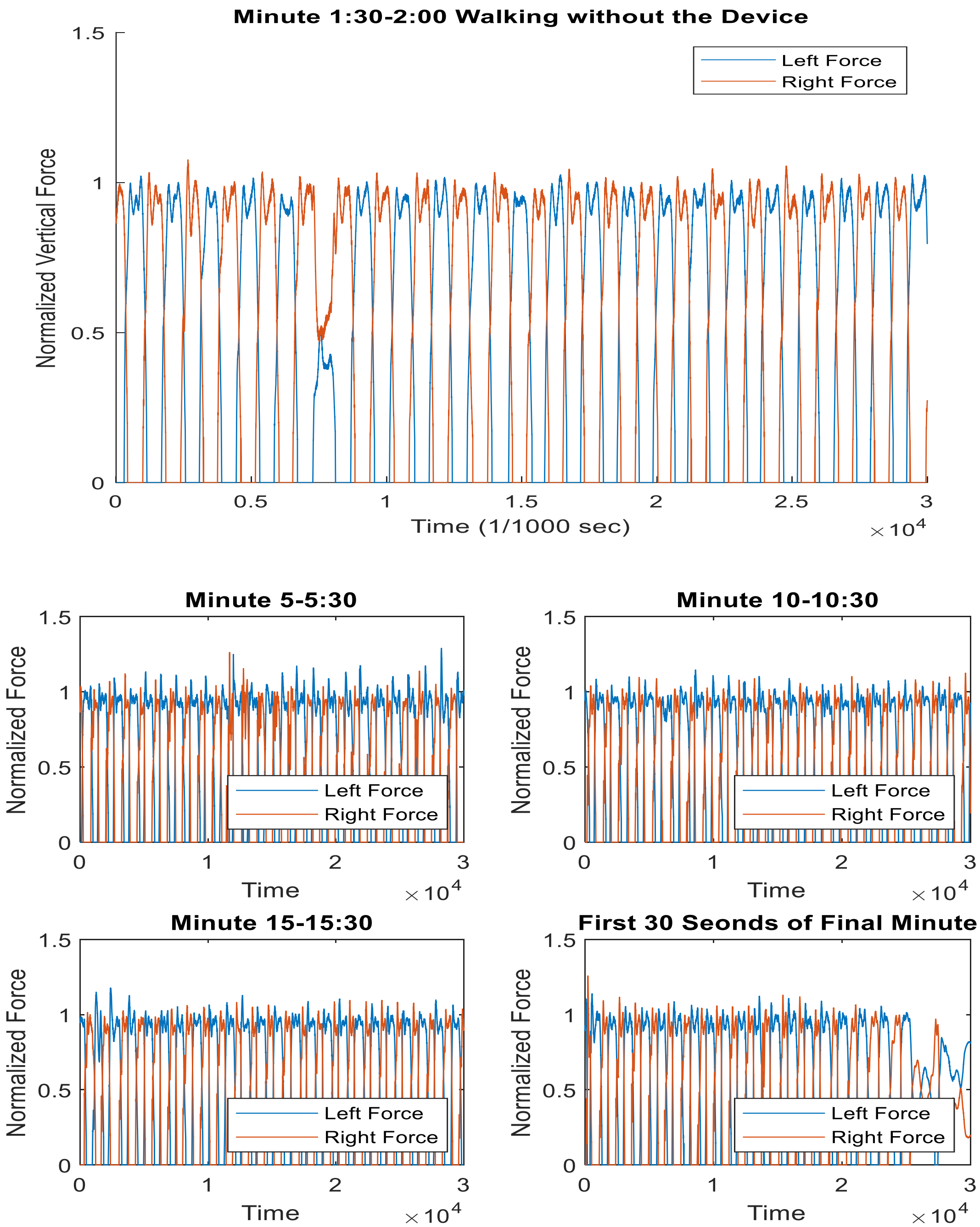

Figure 3.7: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 3, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

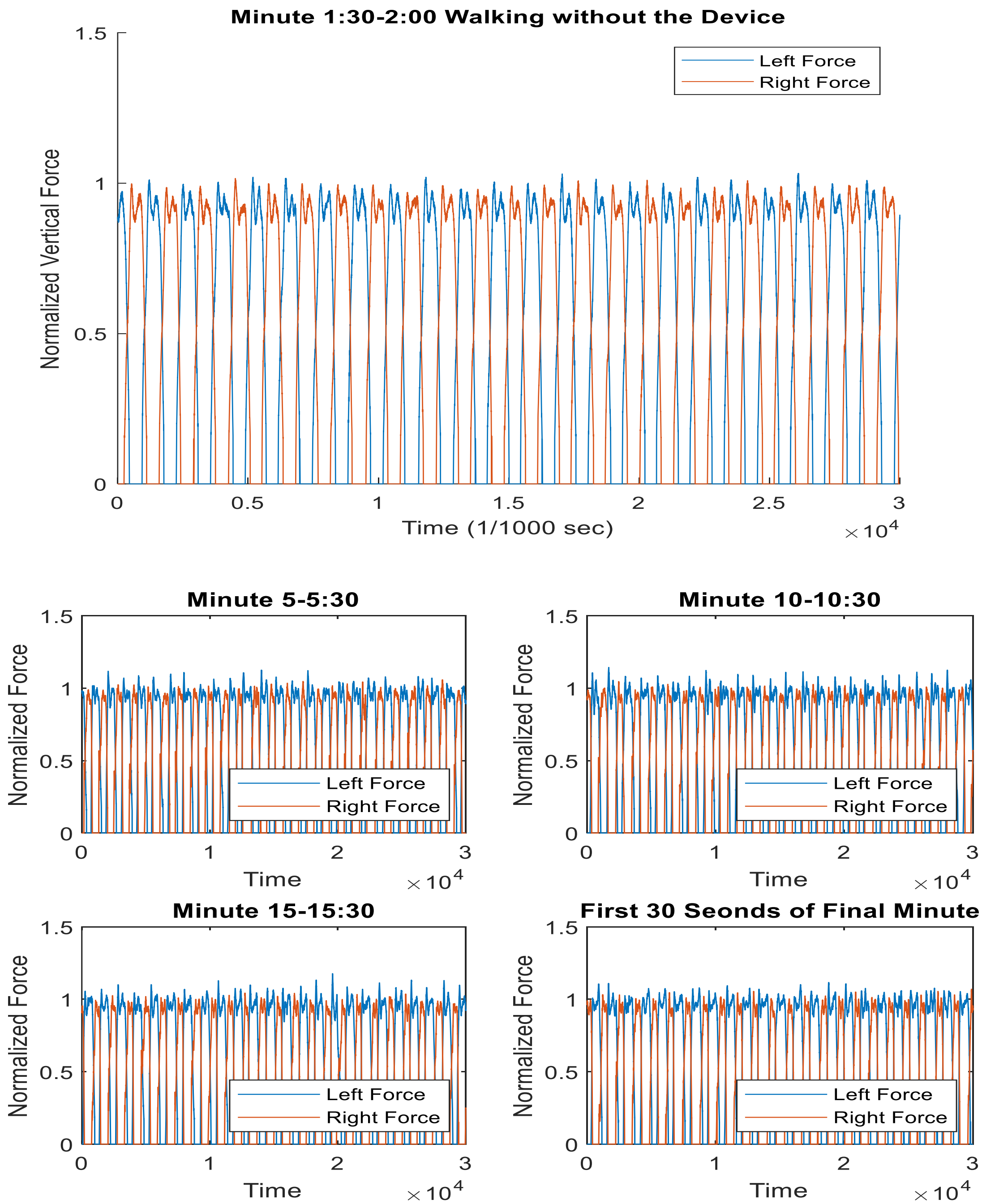

Figure 3.8: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 4, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

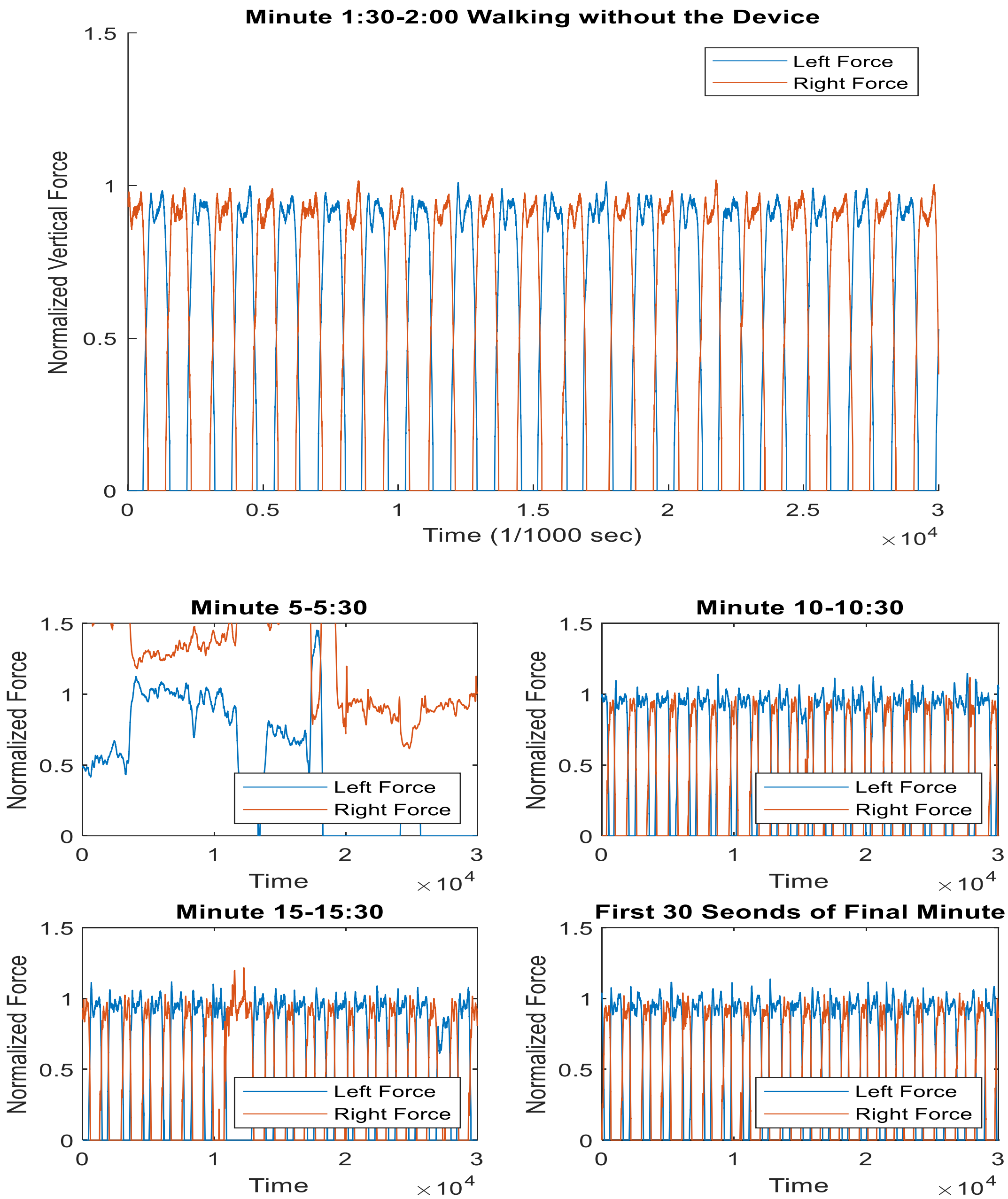

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Figure 3.9: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 5, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5^{th}, 10^{th}, 15^{th}, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

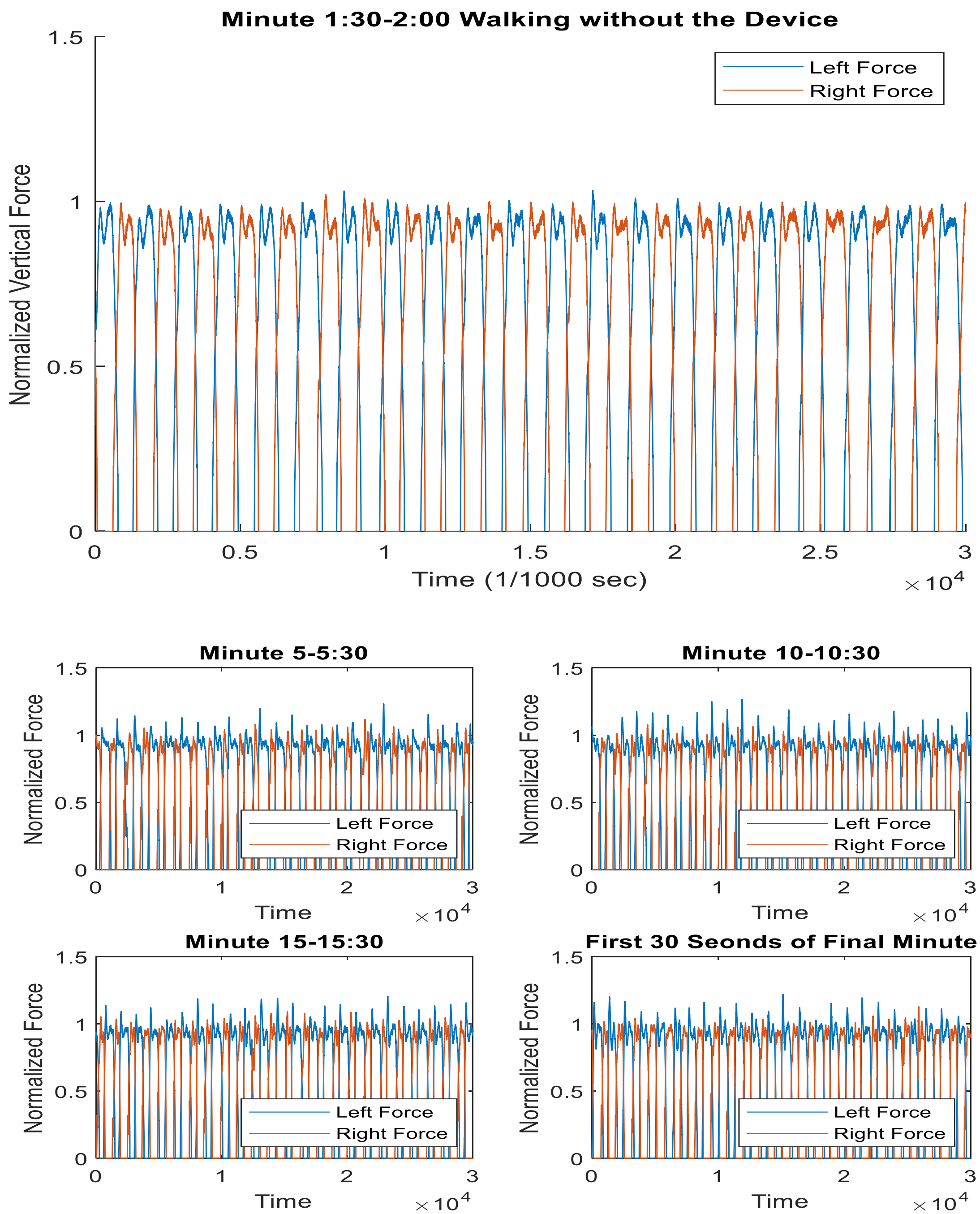

Figure 3.10: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 6, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5^{th}, 10^{th}, 15^{th}, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

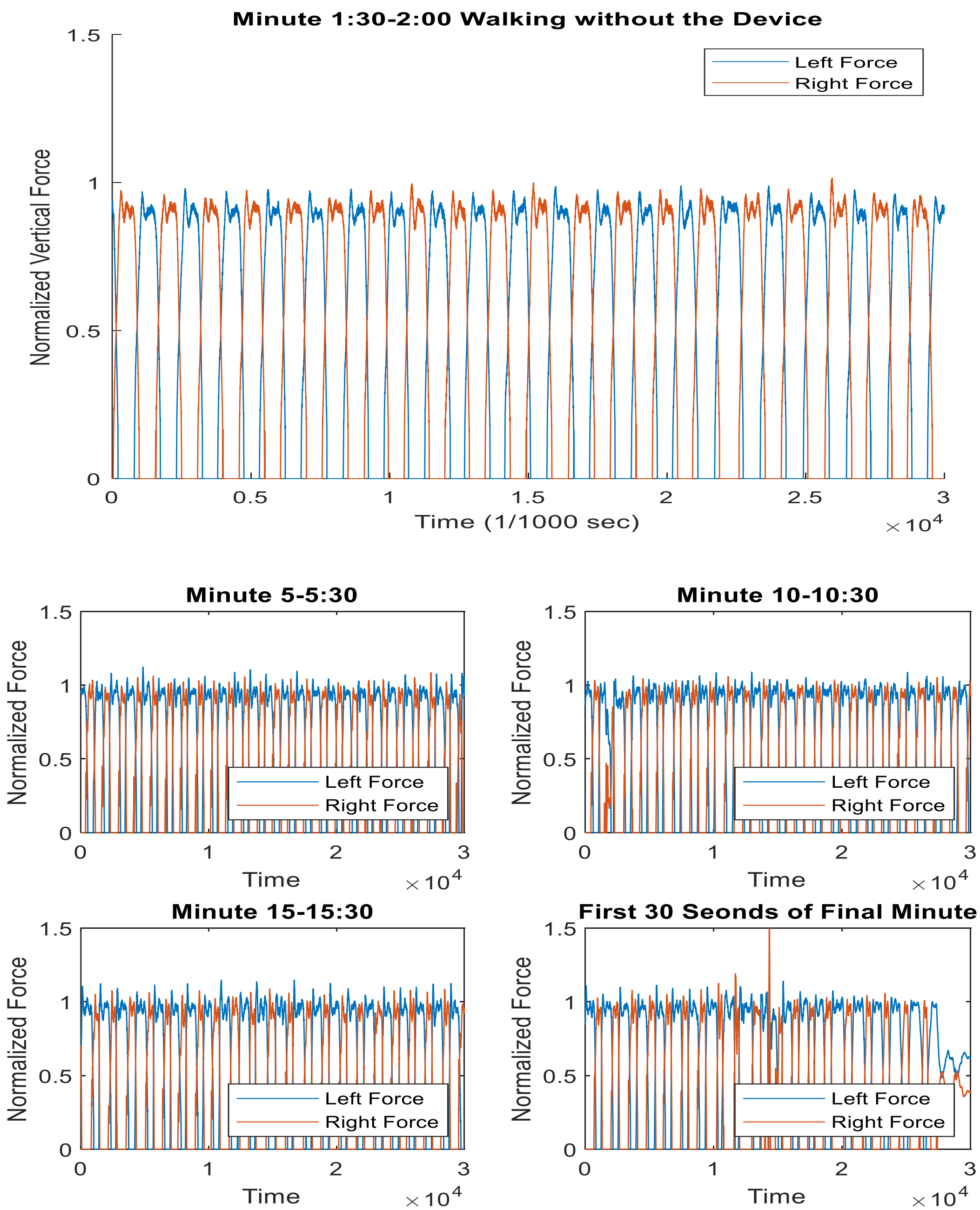

Figure 3.11: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 7, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

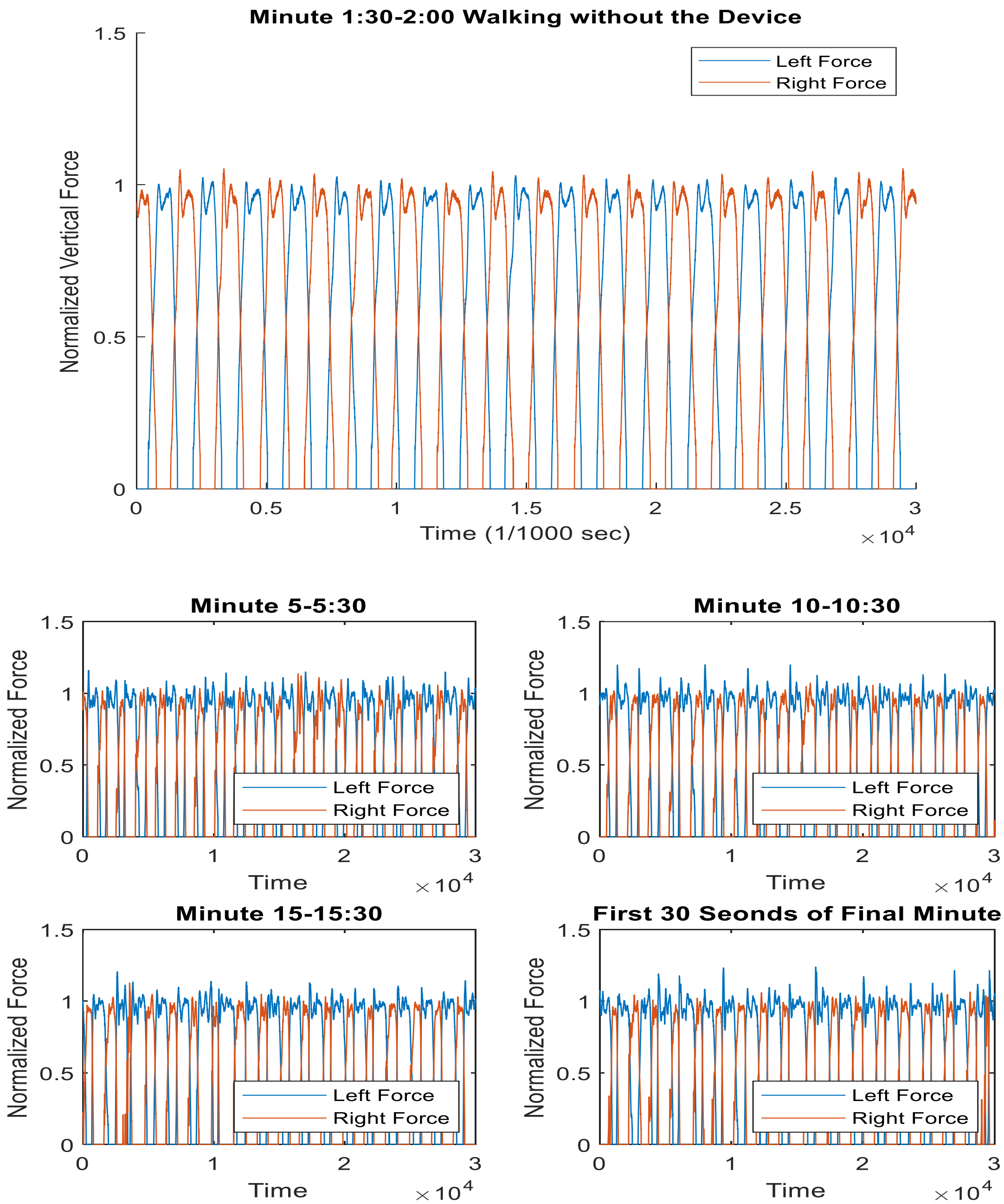

Figure 3.12: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 8, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

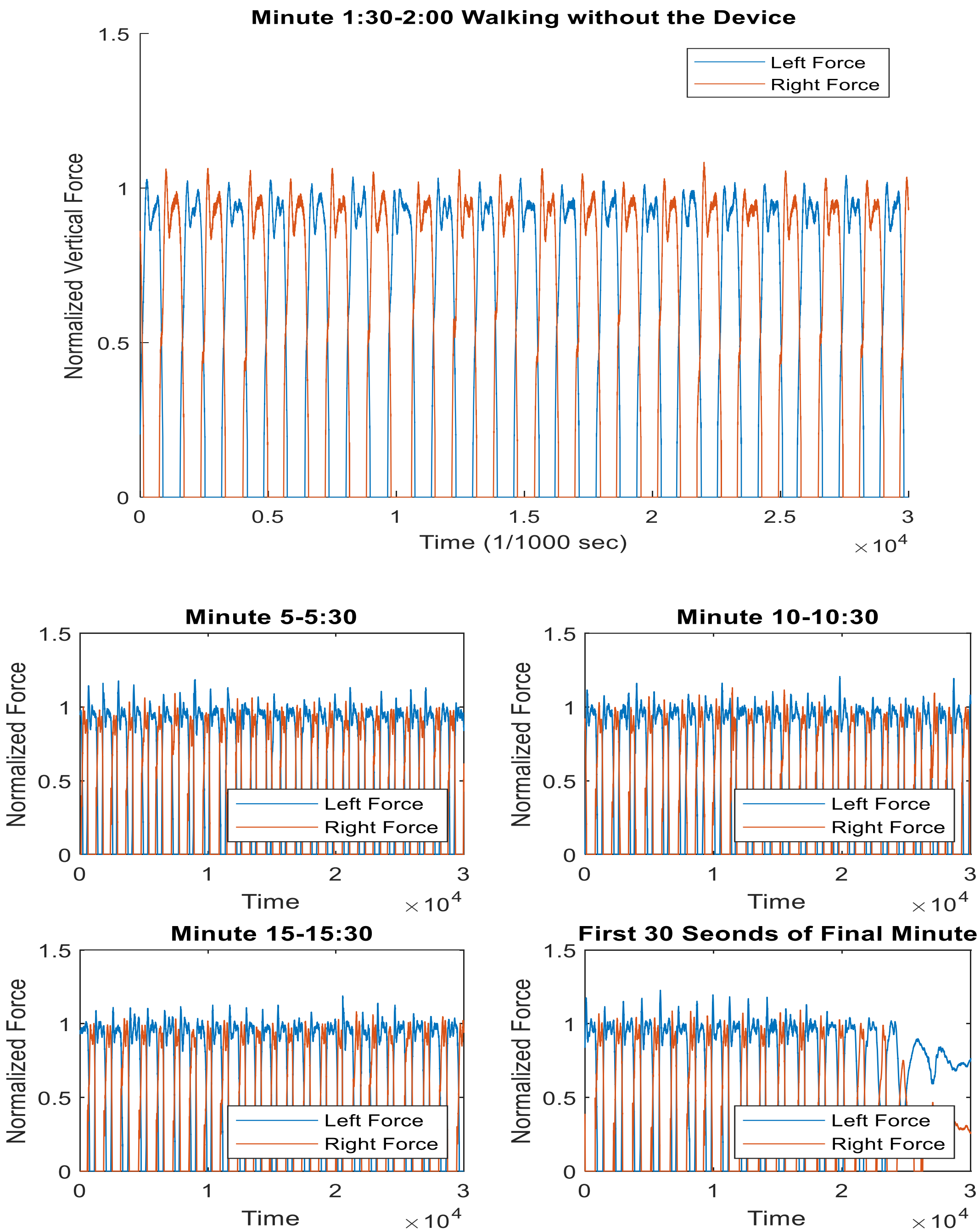

Figure 3.13: Top panel: Normalized, by body weight, vertical (Z) ground reaction forces, of subject 9, during the walking trial without the device during the 30 second time from of 1:30-2:00. Bottom four panels: Subplot of normalized vertical ground reaction forces over 30 second intervals at the 5th, 10th, 15th, and the last minute of all walking trials wearing the device. Each peak represents another step. The stance of the step is when the vertical force is greater than the 100 N threshold. The left leg is always free and the device is worn on the right leg in those such trials.

3.4. How symmetry changes with experience

We see that subjects become more symmetric compared to the first few minutes, although the trend is not consistent over all time. Figures 3.14-3.22 below evaluate the symmetry of each subject walking with the device in 5% intervals from 10% to 100% of the time for the combined trials walking with the device for each subject. Data marked at each point is the mean asymmetry from all data at that percentage and 5% before. For example, at the 10% interval, data is averaged from 5% to 10% of the total time walking with the device. The plots also show a vertical line representing when the speed increased from V_1 to V_2. The horizontal line represents the asymmetry of the subject when walking without the device, which is the mean of the right force per the mean of the total force for all points in trial 2, this is considered the measured stability of the subject.

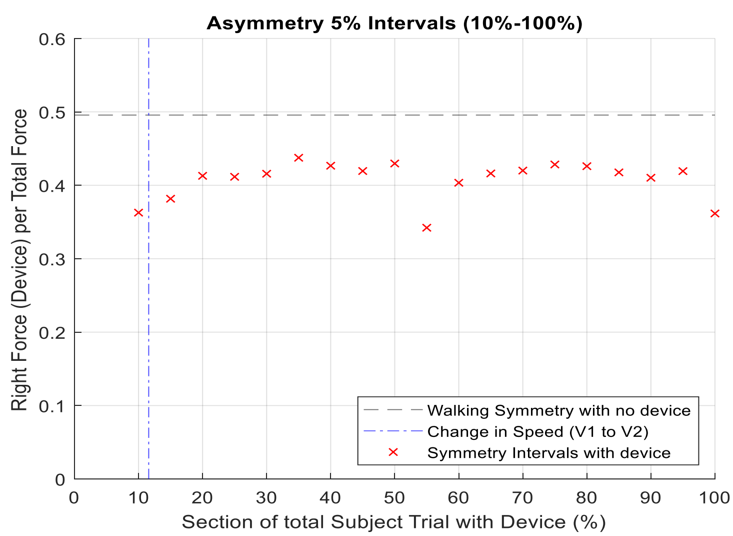

Figure 3.14: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 1. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

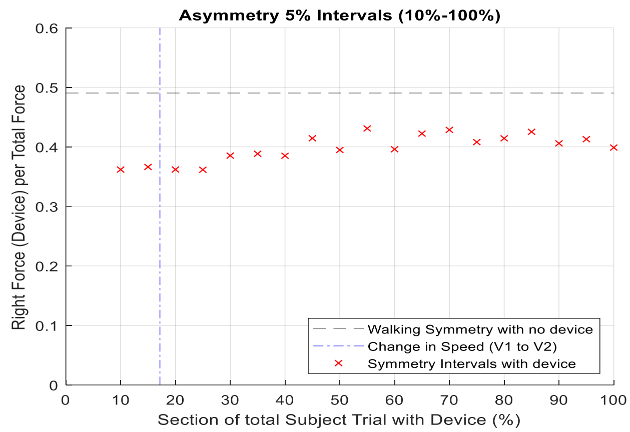

Figure 3.15: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 2. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

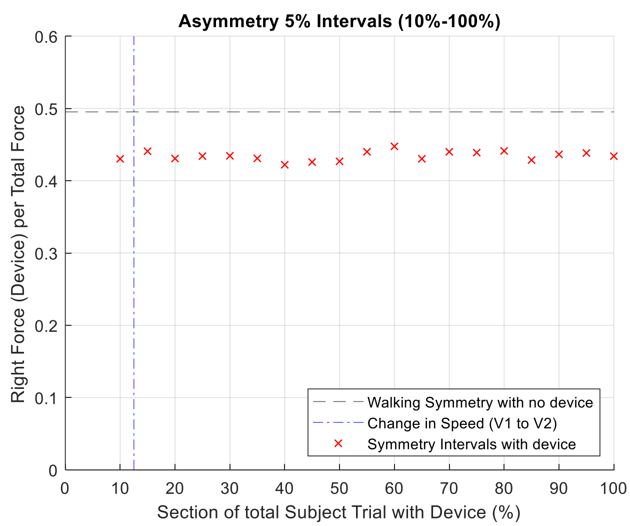

Figure 3.16: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 3. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

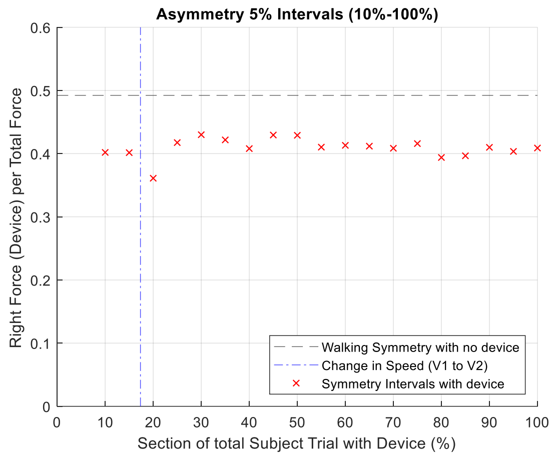

Figure 3.17: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 4. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

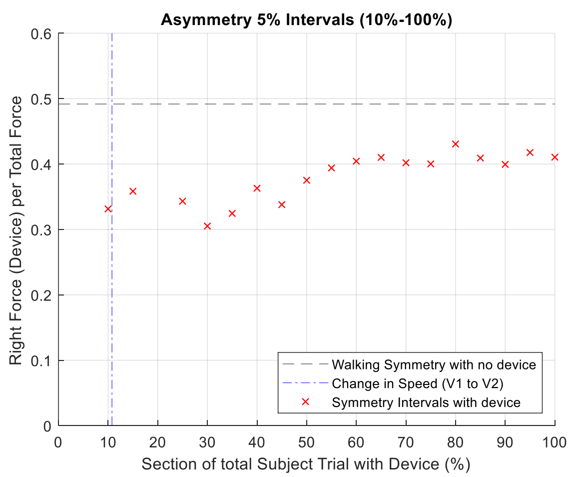

Figure 3.18: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 5. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

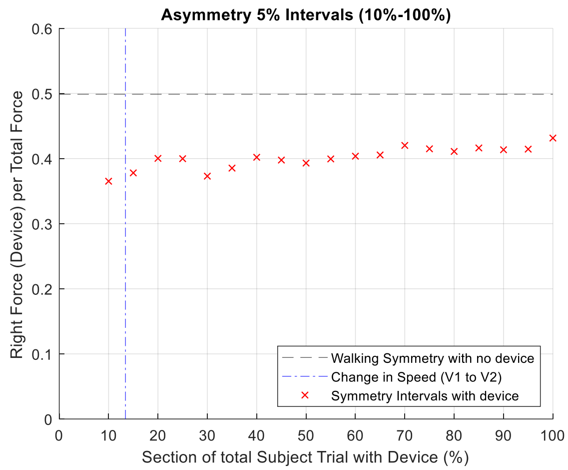

Figure 3.19: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 6. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

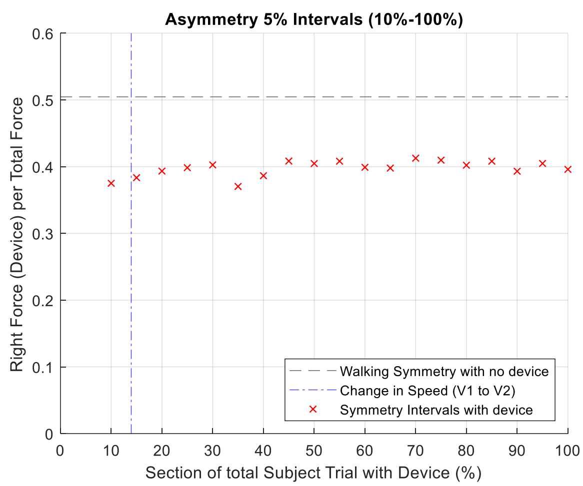

Figure 3.20:Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 7. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

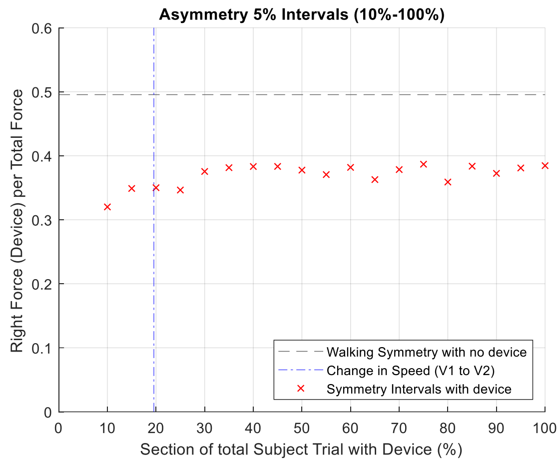

Figure 3.21: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 8. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

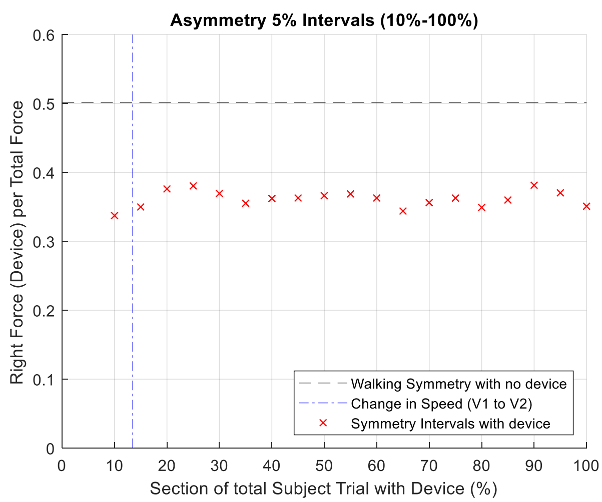

Figure 3.22: Symmetry index (average of the right force divided by the average of the total force) of subjects when walking with the device in 5% intervals of all such trials from 10% to 100% of the time of the trial for subject 9. The vertical line represents the change from velocity 1 to velocity 2 and the horizontal line represents the asymmetry of the subject walking without the device. The device is attached to the right leg in trials walking with the device and the left leg is free in all trials.

Chapter 4 : Discussion

4.1 Overview of Results

During walking trials where the subjects wore the unilateral prosthesis, all subjects exerted greater forces with their left (free) leg, thus bearing more of the body weight with the free leg. The average asymmetry, right (device) force over total force, for such trials was 0.3960 with a standard deviation of 0.0217. On average, the fraction of right leg force (with device) of the total force (symmetry index) while wearing the device was 0.1002 less than when not wearing the device. Plotting how symmetry changes with time and experience, we find of the nine subjects analyzed, all but one had increased symmetry at the end compared to the first 5% of the walking gait. The most visual systematic increase in symmetry was found in subjects 2, 5 and 6.

We also evaluated symmetry in stance times. During the walking trial without wearing the device, the average stance time of all subjects was 0.898 seconds on the left side and 0.885 seconds on the right. For all trials walking with the device, for all subjects, the time for the left side was larger than the time for the right side. The average difference for such trials was 0.310 seconds.

The symmetry results standing study performed with the iWALK 2.0 by Robert Shepherd were not similar to the walking study done here. In the standing study, subjects started the trial by distributed less force on the prosthetic leg (about 40% on average). By the end of the standing trial subjects would be distributing more force on the prosthetic leg (about 60% on average). Thus, in Shepherd’s standing trials, the symmetries were eventually flipped with higher force distribution from the free leg to the prosthetic leg. In our walking study, subjects started with 30-40% of the force distributed to the prosthetic leg. For all but one subject the percentage of force distributed to the prosthetic leg increased, but never even reached the percentage of force distributed to the right leg when walking without the device (about 50% “symmetric”). So, the results of these two studies are significantly different in regard to symmetry. In standing, subjects eventually distribute more force on the prosthetic leg, while in walking, subjects increase the percentage of force on the prosthetic, but it does not ever exceed 50% (more force than the free side).

4.2 Implications of the Work

This study allows us to see how subjects approached walking with a device that they had never used before, simulating a relearning process of walking. With knowledge of how a human relearns to walk, modifications and advancements could be made to assistive walking devices such as exoskeletons. As we learned from Zhang et al (2017), exoskeletons are can be successfully used for walking assistance and rehabilitation, but there is room for improvement. Understanding more of how humans learn to walk may allow for a more optimized design of an exoskeleton. This knowledge may also be useful in general rehabilitation of subjects with injuries prohibiting walking. Understanding how humans approach a new situation can be useful for approaching methods of their recovery. Potentially, understanding how humans learn to walk with an unknown unilateral prosthesis may aid in the development of human-like robotics. Knowledge of how humans learn can be useful to designing the feedback system in robotics to represent that of a human more closely.

4.3 Limitations of the Work

Subject population was limited to 10 subjects, and analysis was limited to 9 subjects due to data processing issues for the tenth subject. To gain a better understanding of the learning process, it would be beneficial to have many more subjects. Subjects walked for only 20 minutes wearing the device due to time constraints and the difficulty of using the device for the first time. Data was only collected for subjects walking with the device worn on the right leg, not the left. Evaluating how subjects respond to learning on the left versus right leg could bring a better understanding.

Subject age ranged only between 19 to 22, only a three-year range. Evaluating how different age groups were to perform would have been helpful to this study, especially for use in rehabilitation. While both force and motion data were collected in this study, only force data was analyzed; the motion data was not analyzed due to time constraints and due to larger computational resources needed for longer motion capture files. The device used for this study, the iWALK 2.0, is an inexpensive unilateral prosthesis. Using a higher quality, more stable/robust device could benefit the comfort of the subjects and therefore help to accelerate the learning process, providing better more useful data. The fitting of the device became an issue for eight of the ten subjects (needed to adjust fit during 20-minute trial). Due to the strap mechanism of the device, the straps could easily loosen. This caused discomfort and the need to stop and readjust the device for the subject.

Chapter 5 : Conclusion and Future Work

Ground reaction force data and motion capture data was collected from ten subjects during walking trials. Subjects were first evaluated walking normally and then evaluated walking with a unilateral prosthesis, the iWALK 2.0, worn on their right leg. The experiments showed that the subjects walked asymmetrically with the device placing more load on average on the free leg and spending less stance time on the prosthesis leg. We also saw trends toward greater symmetry in most subjects, at least comparing initial and final few minutes of walking. In future studies, the Likert scale can be used to survey the subjects after completing the trials for an accurate understanding of their experience.

In future work, we hope to perform many more detailed analyses of symmetry and its evolution from different perspectives. For instance, whereas here, we simply gaged symmetry visually and through means, we can statistically test the symmetry at different stages of the trial (beginning, end, etc.), specifically testing for statistical significance, for instance, using t-tests. The most direct extension of this study is to analyze the motion capture data from the Vicon system. Motion capture data can provide a visual understanding of the subjects walking patterns and how those patterns may have changed. Motion data could provide the step length for each subject, with and without the device, along with many other important measures of stability. For instance, motion capture data can help us estimate how walking control strategies have changed and step-to-step stability changes over time (Perry and Srinivasan, 2017, Seethapathi and Srinivasan, 2019, Joshi and Srinivasan, 2019).

Making simultaneous use of the motion capture data and the ground reaction force data, we can perform inverse dynamics, thus estimating the torques at each joint for the person. This will allow us to see how joint torques and joint loads change with time, as the person gains more walking experience with the device. Fusing the joint torque information and the motion information, we can estimate the work done by each joint, and thereby estimating the effort of walking from the collected data. We hypothesize that the effort goes down with time. An alternative approach to effort estimation is the so-called indirect calorimetry, using oxygen and carbon dioxide flux during respiration.

Additionally, performing more and longer trials with more subjects can add to the quality of the available. The more data available, the more powerful and generalizable the analysis becomes. With a larger population, the conclusions from the study could have applicability to a greater diversity of the population. With longer trials, the subjects have more of a chance to learn the device. A future study could feature subjects returning for multiple timed sessions, allowing them to have more time walking in this adverse situation. Additionally, trials can be performed on both the left and the right leg for a better understanding of each subject. By adding ambulatory sensors on the device and the person (perhaps IMU based), we could potentially track subjects over a longer period of time, perhaps many days. For instance, when a subject is using the device to recover from a strained ankle (the original purpose of the device), we could track them for days to see their gait improvement over many days.

There is potential performing a similar study using a different device. As mentioned before, the iWALK 2.0 is an inexpensive device, but lacks comfort and some stability. Often during this study (eight out of ten subjects), subjects needed to stop during trials walking with the device for a readjustment or for a break due to discomfort using the device. When the adjustable straps are not become lose, the device is very hard to use and becomes very uncomfortable. A higher quality device with a more secure attachment to the person may provide better results because it could give the subjects an easier and more comfortable experience.

References

[1] A.D.A.M. Inc., & URAC. (2017, February 23). Walking abnormalities: MedlinePlus Medical Encyclopedia. Retrieved May 7, 2019, from https://medlineplus.gov/ency/article/003199.htm

[2] Assaiante, C., Mallau, S., Viel, S., Jover, M., & Schmitz, C. (2005). Development of Postural Control in Healthy Children: A Functional Approach. *Neural Plasticity*, *12*(2-3), 109–118. doi: 10.1155/np.2005.109

[3] Chen, Q., Cheng, H., Yue, C., Huang, R., & Guo, H. (2017). Step length adaptation for walking assistance. *2017 IEEE International Conference on Mechatronics and Automation (ICMA)*. doi:10.1109/icma.2017.8015892

[4] Mekki, F., Borghetti, M., Sardini, E., & Serpelloni, M. (2017). Wireless instrumented cane for walking monitoring in Parkinson patients. *2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA)*. doi:10.1109/memea.2017.7985912

[5] Perry, J. A., & Srinivasan, M. (2018). Walking with wider steps changes foot placement control, increases kinematic variability and does not improve linear stability. *Royal Society Open Science,4*(9), 160627. doi:10.1098/rsos.160627

[6] Seethapathi, N., & Srinivasan, M. (2019). Step-to-step variations in human running reveal how humans run without falling. *ELife,8*. doi:10.7554/elife.38371

[7] Shepherd, R. (2019). Learning to Stand with a Simulated Prosthesis

(Undergraduate Honors Thesis). The Ohio State University, Columbus, Ohio

[8] Watelain, E. (2017). Movement and Sports Sciences [Abstract]. *Human Gait: From Clinical Gait Analysis to Diagnosis Assistance*,1-4. doi:https://doi.org/10.1051/sm/2017028

[9] Woollacott, M., Burtner, P., Jensen, J., Jasiewicz, J., Roncesvalles, N., & Sveistrup, H. (1998). Development of Postural Responses During Standing in Healthy Children and Children with Spastic Diplegia. Neuroscience & Biobehavioral Reviews, 22(4), 583–589. doi: 10.1016/s0149-7634(97)00048-1

[10] Zhang, J., Fiers, P., Witte, K. A., Jackson, R. W., Poggensee, K. L., Atkeson, C. G., & Collins, S. H. (2017). Human-in-the-loop optimization of exoskeleton assistance during walking. *Science*, *356*(6344), 1280–1284. doi: 10.1126/science.aal5054

Appendix

In the main results (chapter 3), we sometimes present the result figures for just one subject. In this appendix, we record the figures for all other subjects for completeness.

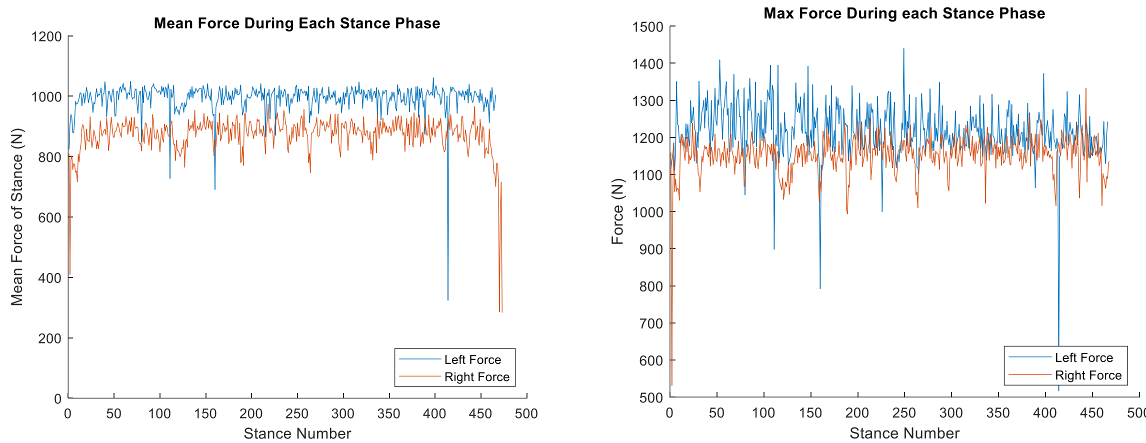

Figure 0.1: Left plot: Mean left and right force during each stance phase for subject 1, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

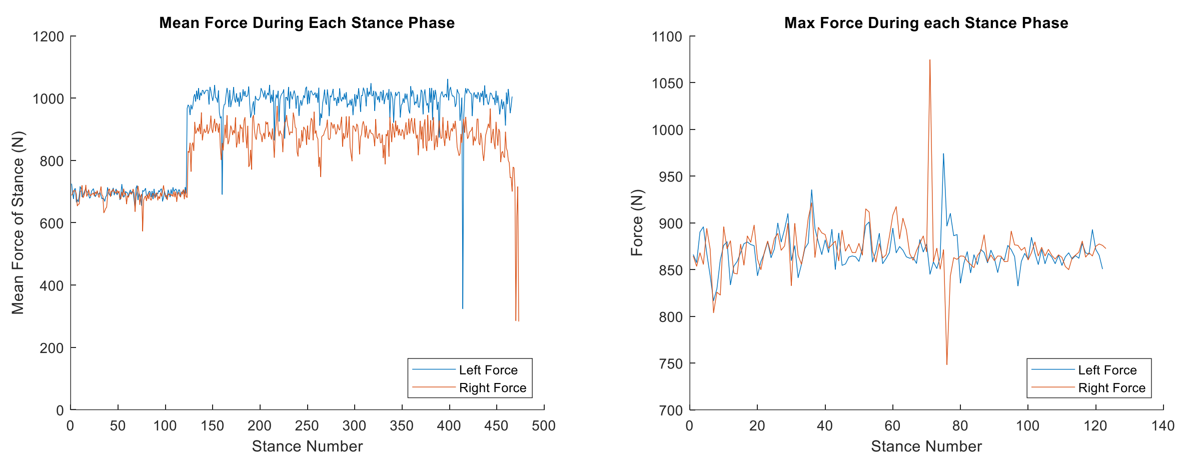

Figure 0.2: Left plot: Mean left and right force during each stance phase for subject 2, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

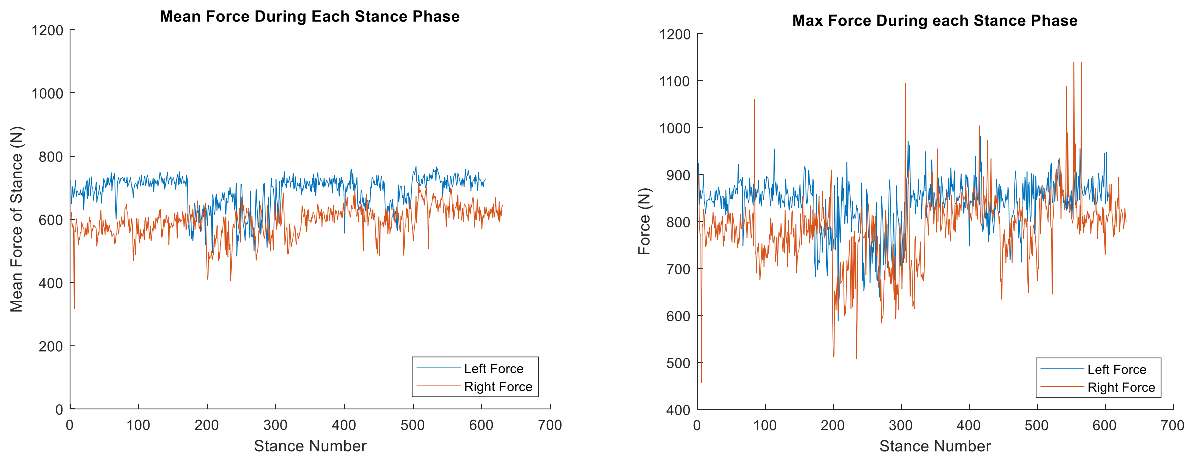

Figure 0.3: Left plot: Mean left and right force during each stance phase for subject 2, for the trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

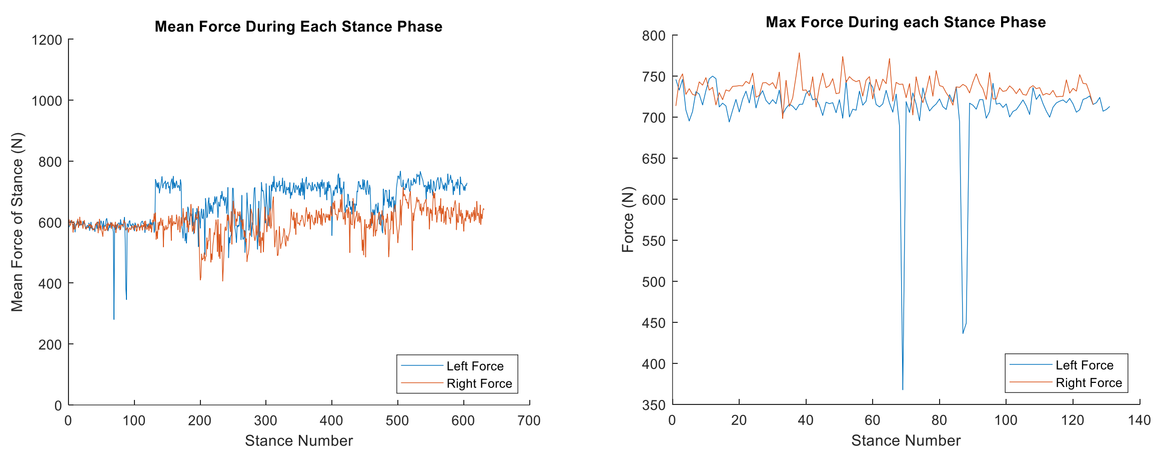

Figure 0.4: Left plot: Mean left and right force during each stance phase for subject 3, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

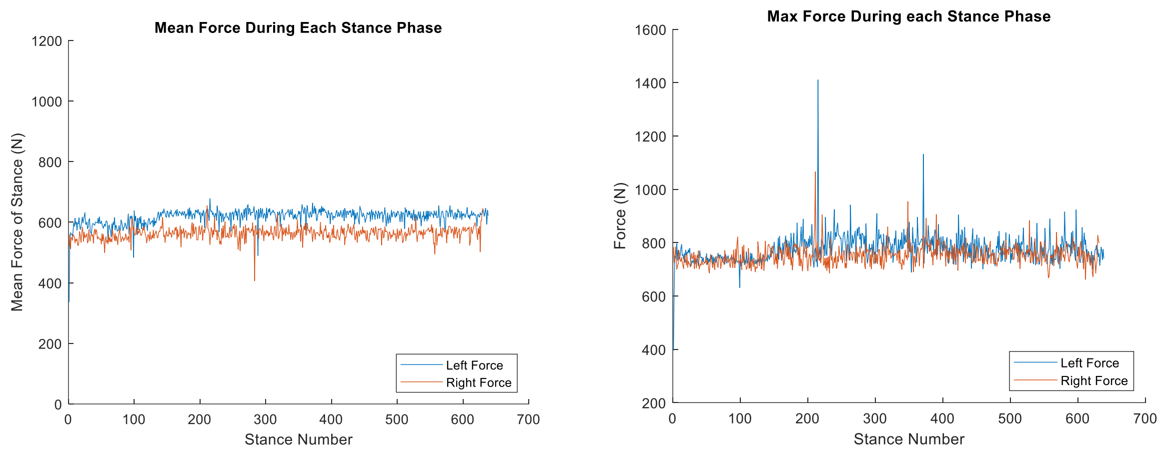

Figure 0.5: Left plot: Mean left and right force during each stance phase for subject 3, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

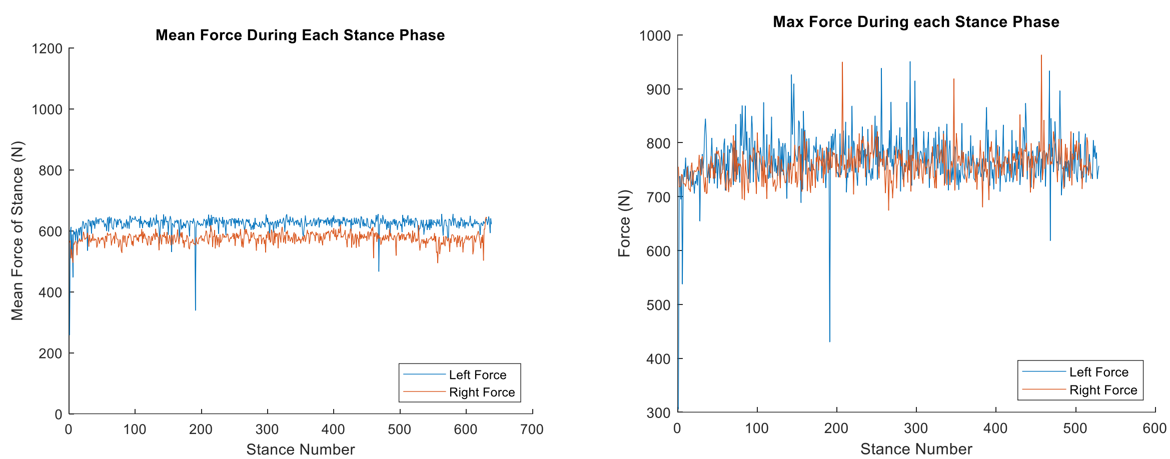

Figure 0.6: Left plot: Mean left and right force during each stance phase for subject 3, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

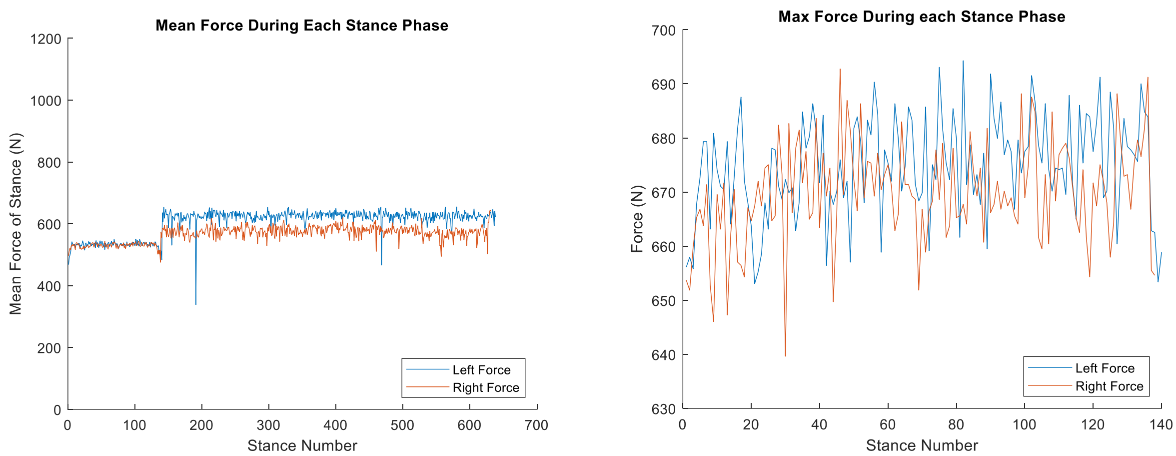

Figure 0.7: Left plot: Mean left and right force during each stance phase for subject 4, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

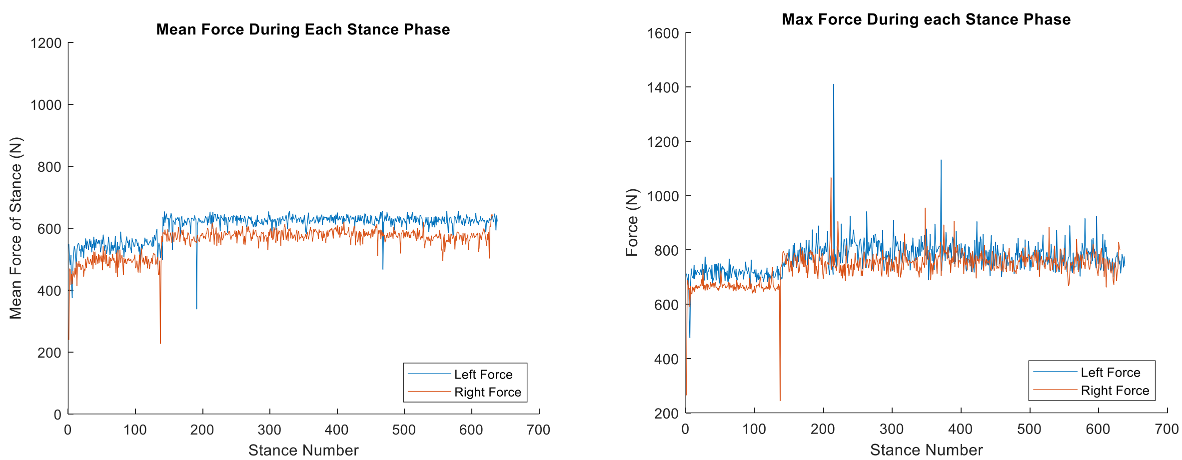

Figure 0.8: Left plot: Mean left and right force during each stance phase for subject 4, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

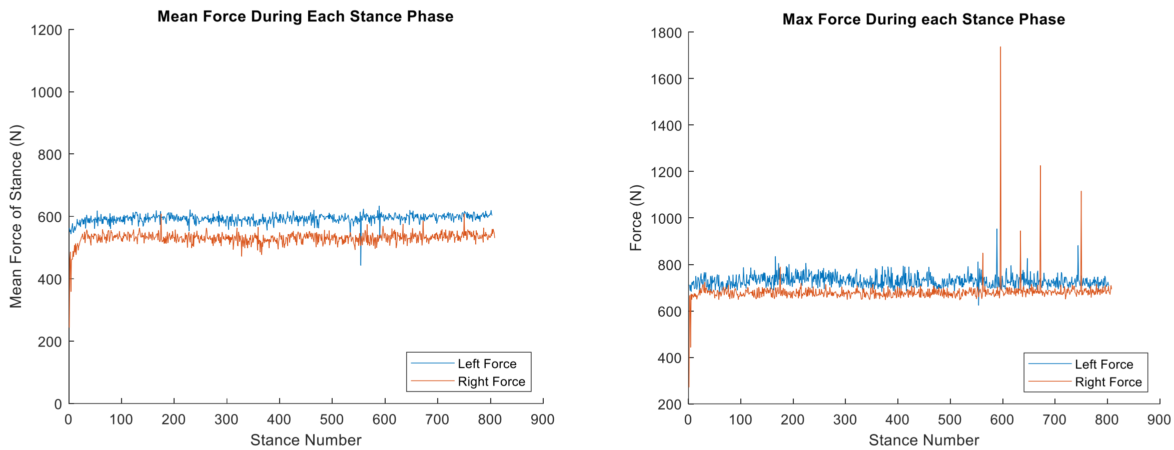

Figure 0.9: Left plot: Mean left and right force during each stance phase for subject 4, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

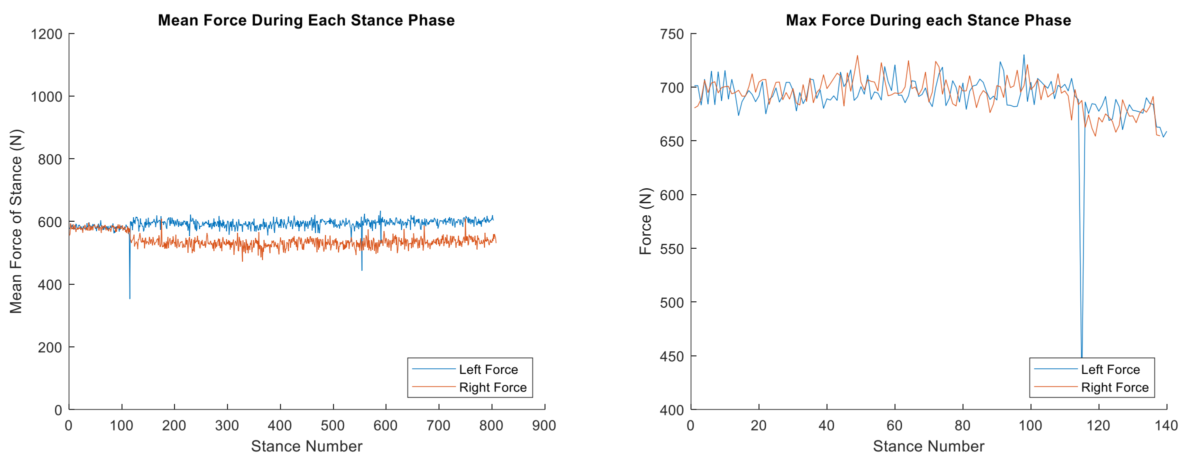

Figure 0.10: Left plot: Mean left and right force during each stance phase for subject 5, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

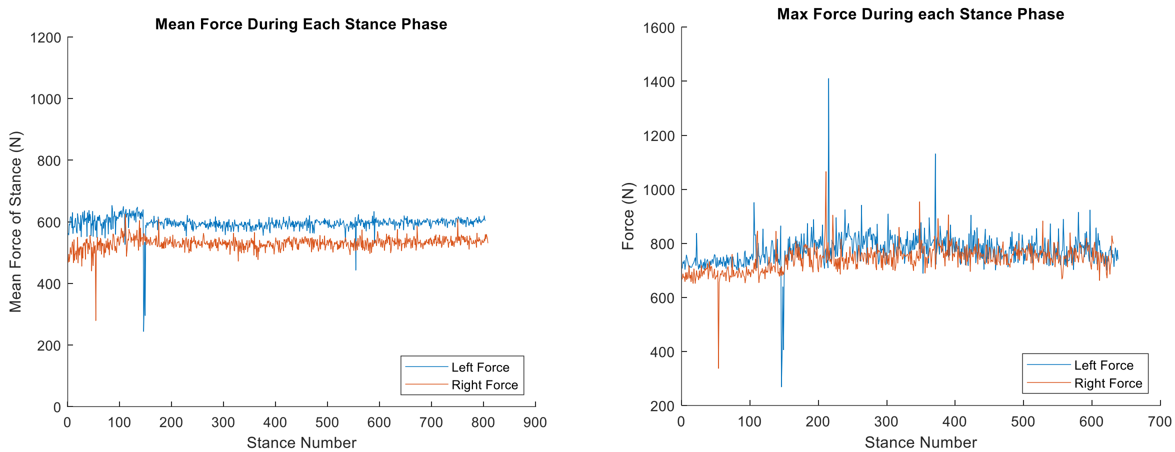

Figure 0.11: Left plot: Mean left and right force during each stance phase for subject 5, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

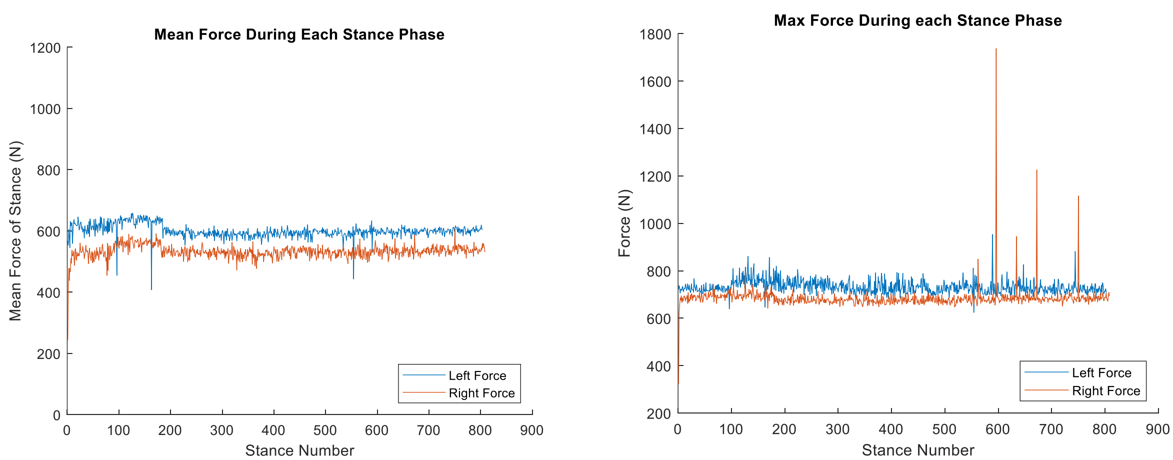

Figure 0.12: Left plot: Mean left and right force during each stance phase for subject 1, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

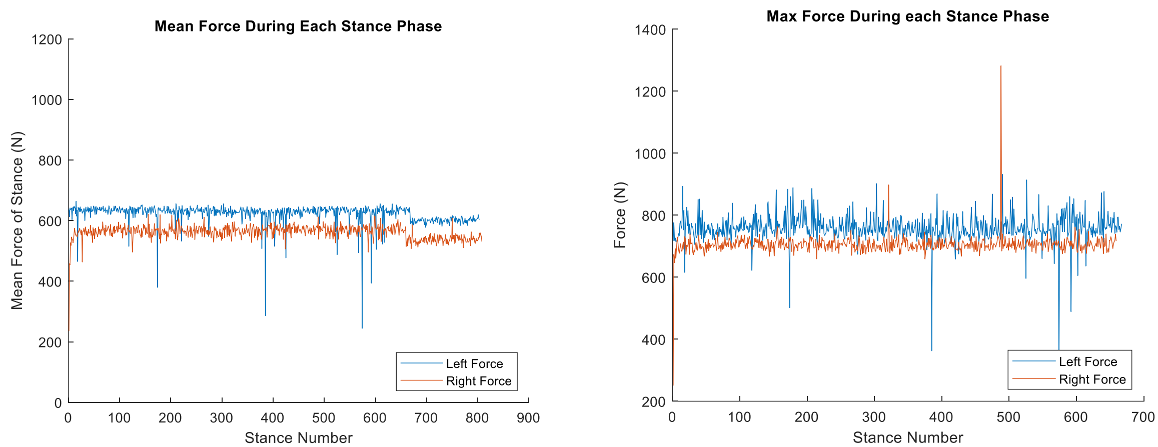

Figure 0.13: Left plot: Mean left and right force during each stance phase for subject 5, for the third trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

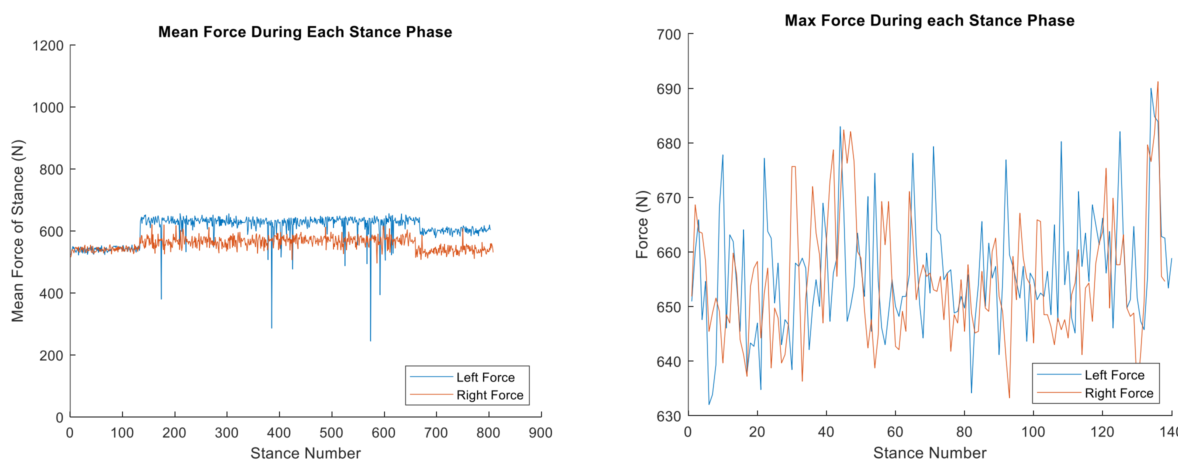

Figure 0.14: Left plot: Mean left and right force during each stance phase for subject 6, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

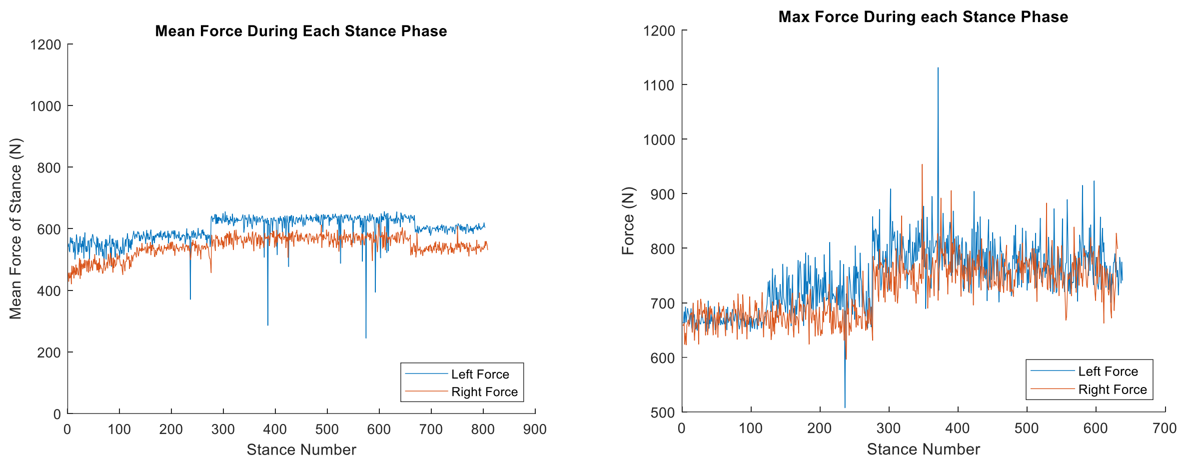

Figure 0.15: Left plot: Mean left and right force during each stance phase for subject 6, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

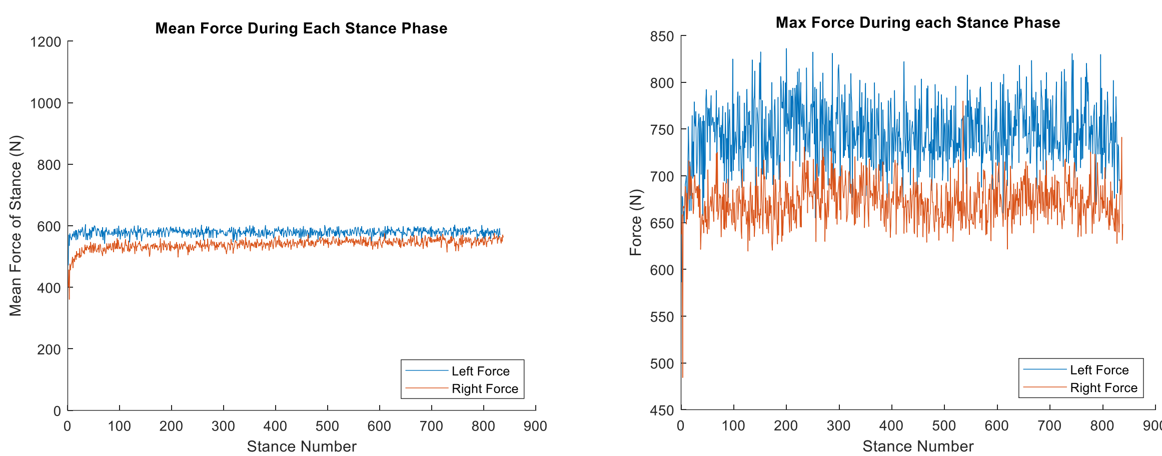

Figure 0.16: Left plot: Mean left and right force during each stance phase for subject 6, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

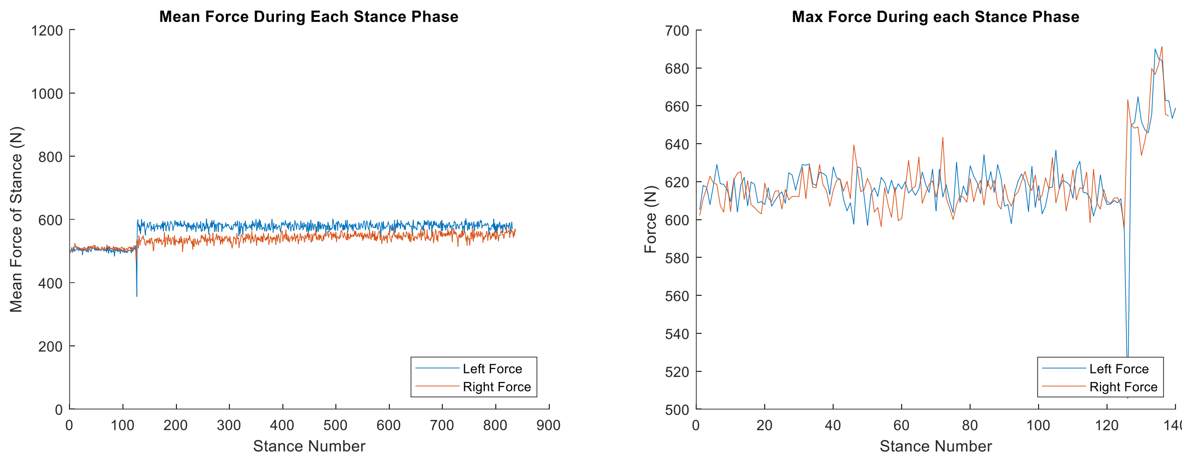

Figure 0.17: Left plot: Mean left and right force during each stance phase for subject 7, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

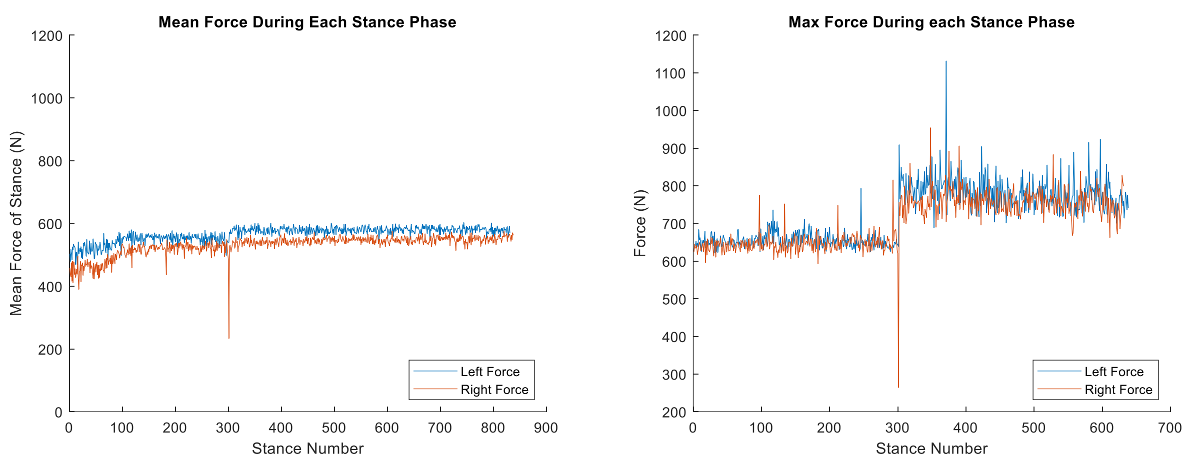

Figure 0.18: Left plot: Mean left and right force during each stance phase for subject 7, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

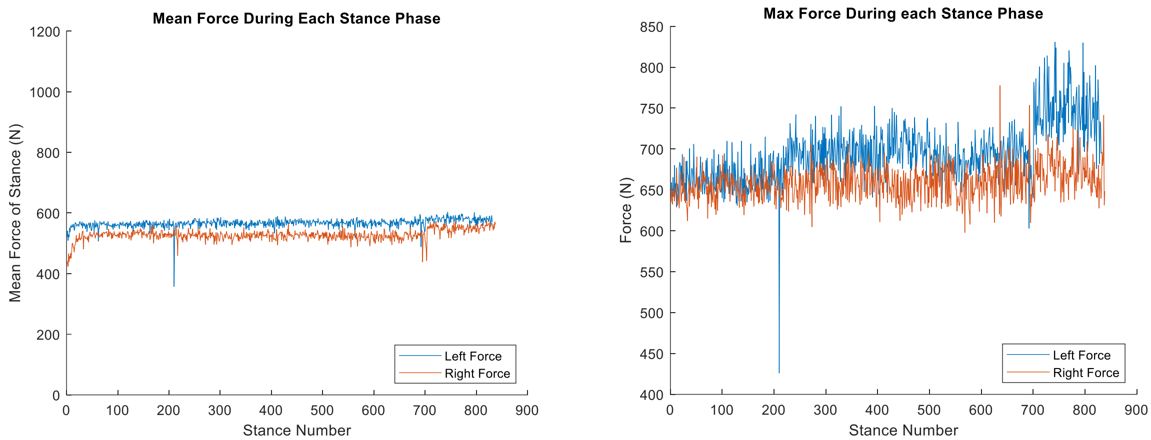

Figure 0.19: Left plot: Mean left and right force during each stance phase for subject 7, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

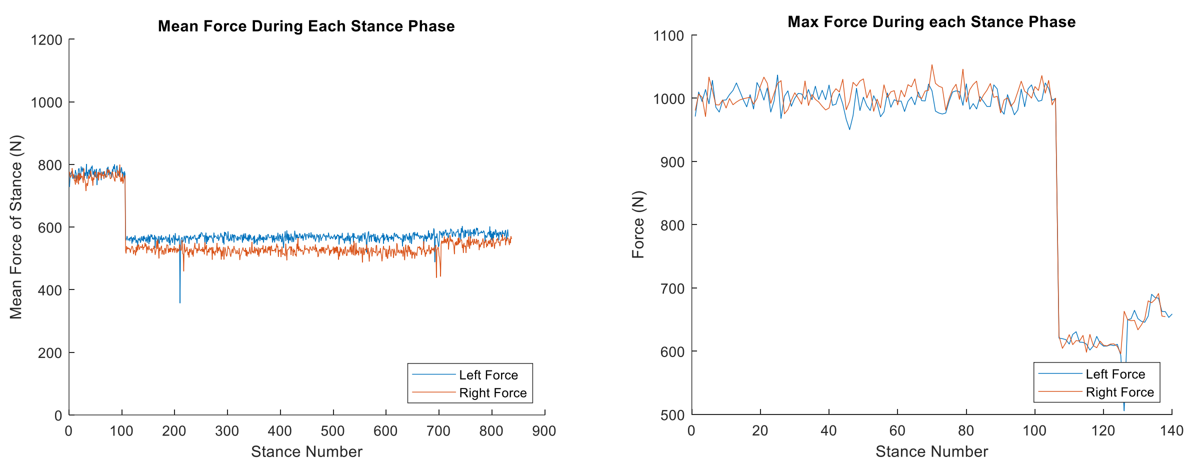

Figure 0.20: Left plot: Mean left and right force during each stance phase for subject 8, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

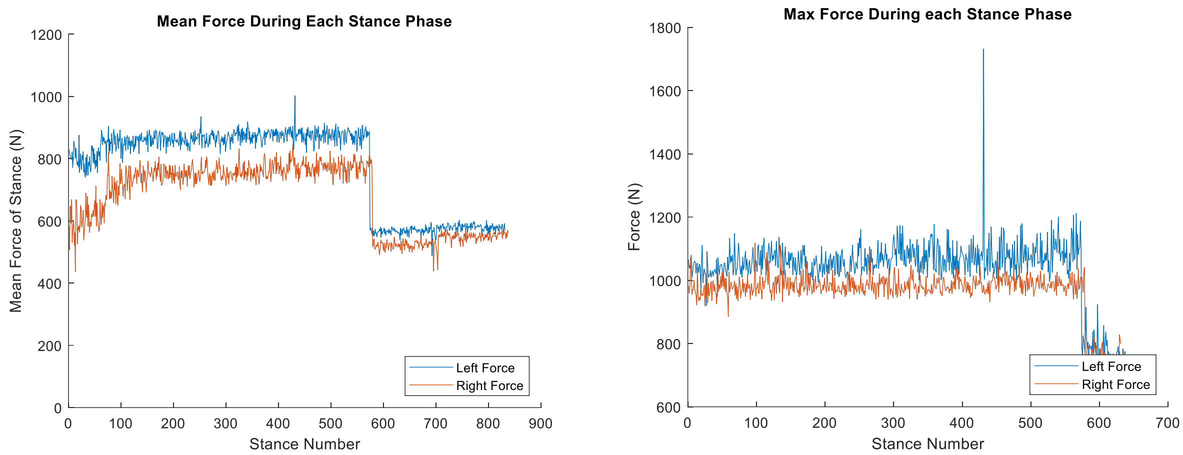

Figure 0.21: Left plot: Mean left and right force during each stance phase for subject 8, for the trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

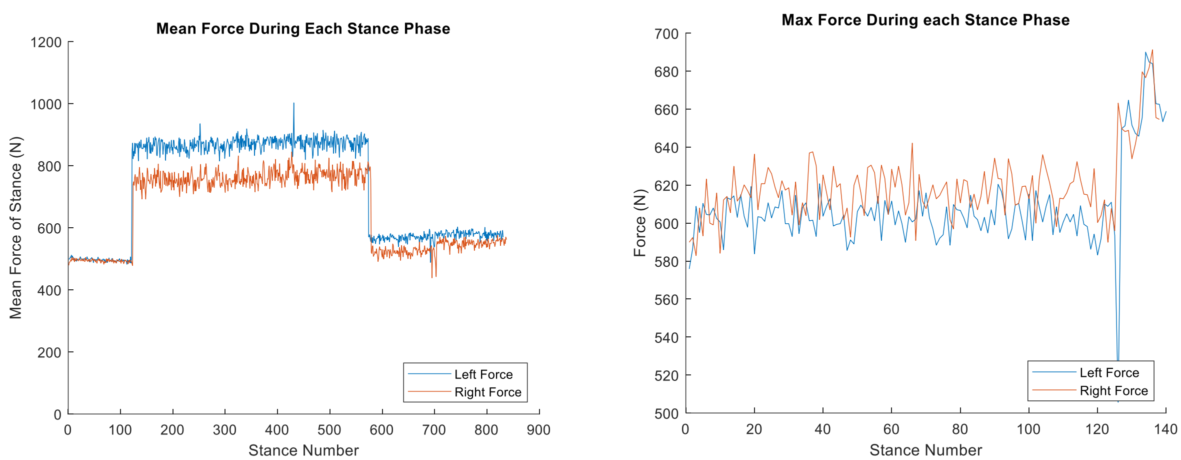

Figure 0.22: Left plot: Mean left and right force during each stance phase for subject 9, for the trial walking while not wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

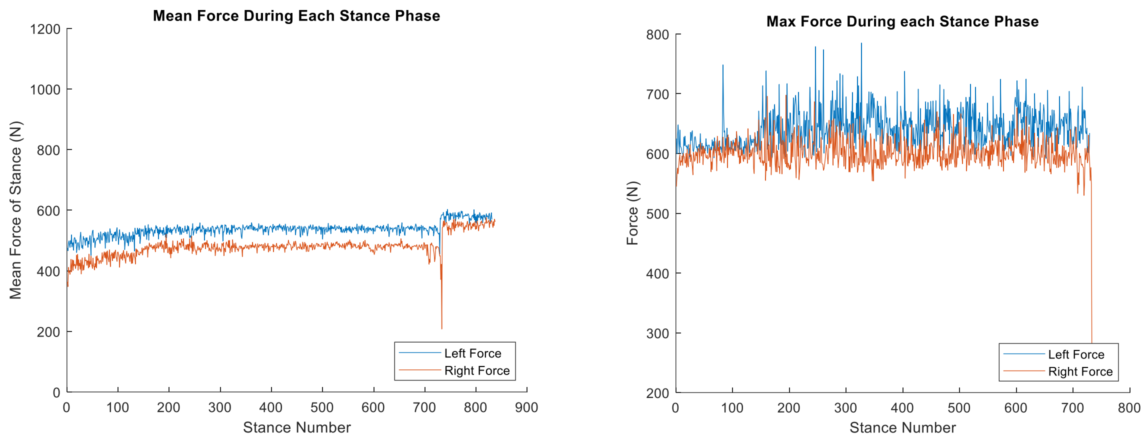

Figure 0.23: Left plot: Mean left and right force during each stance phase for subject 9, for the first trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

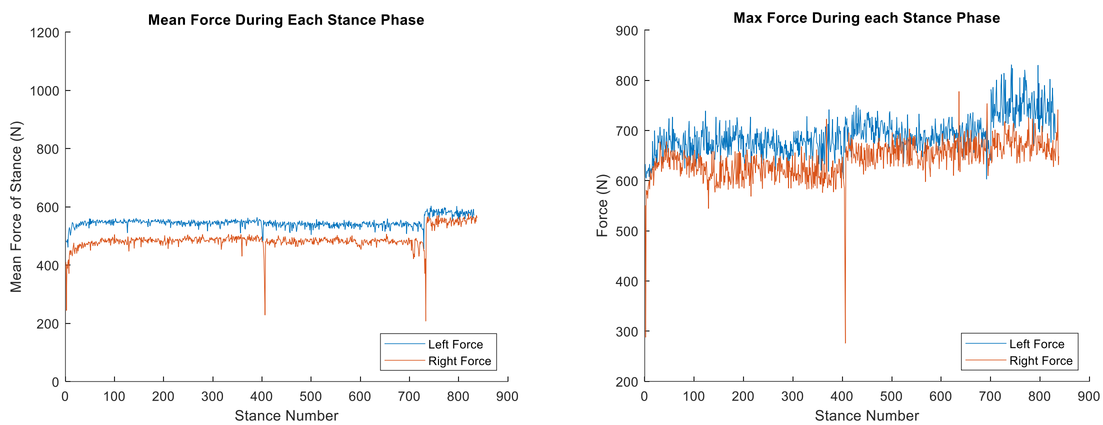

Figure 0.24: Left plot: Mean left and right force during each stance phase for subject 9, for the second trial walking while wearing the device where the device is worn on the right leg. Right plot: Max left and right force for each stance during the discussed trial.

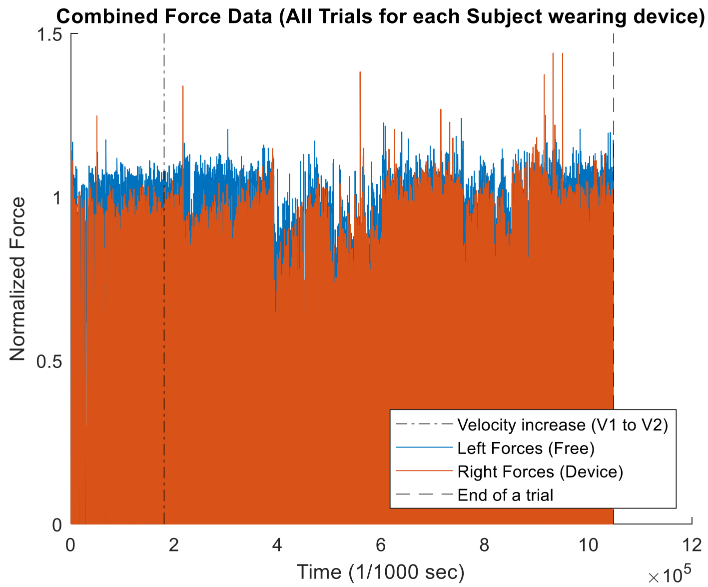

Figure 0.25: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 2, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

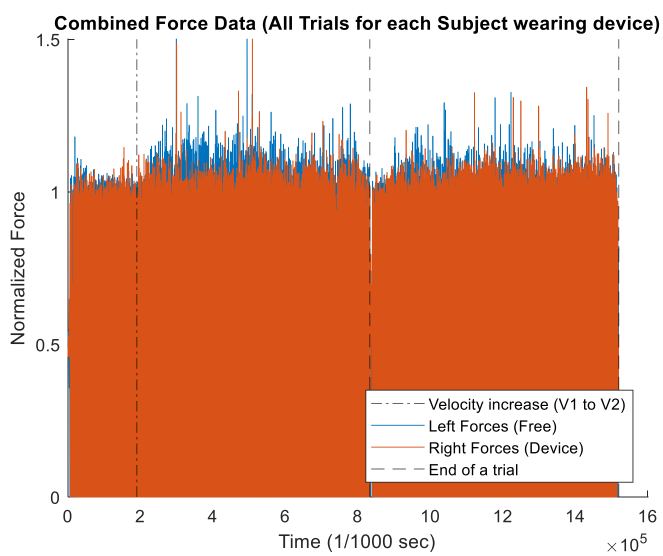

Figure 0.26: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 3, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

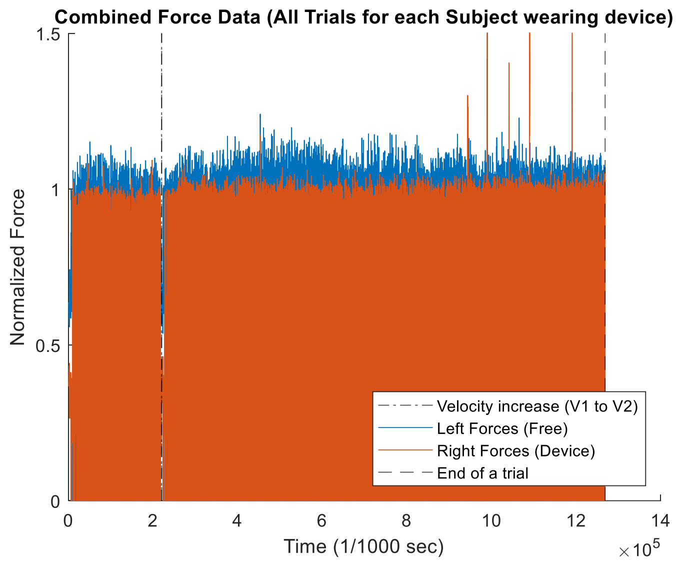

Figure 0.27: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 4, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

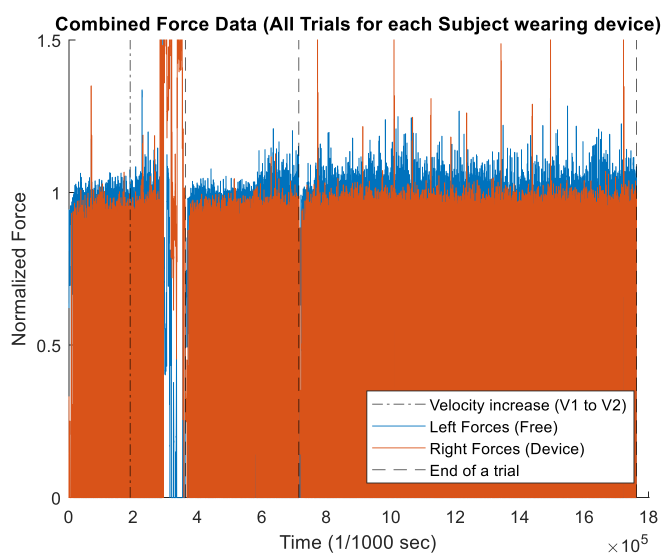

Figure 0.28: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 5, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

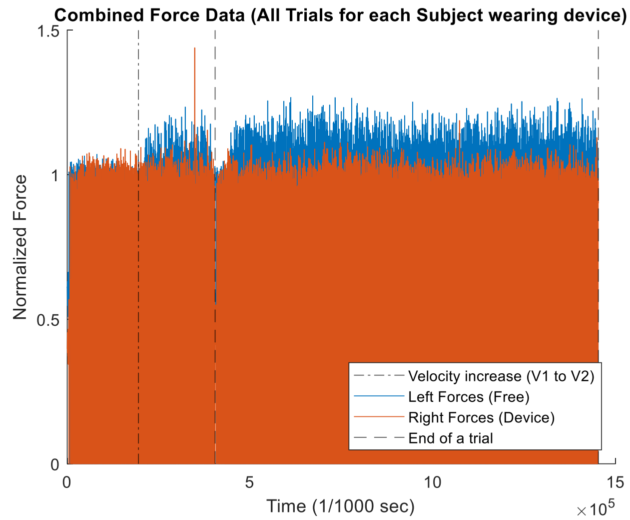

Figure 0.29: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 6, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

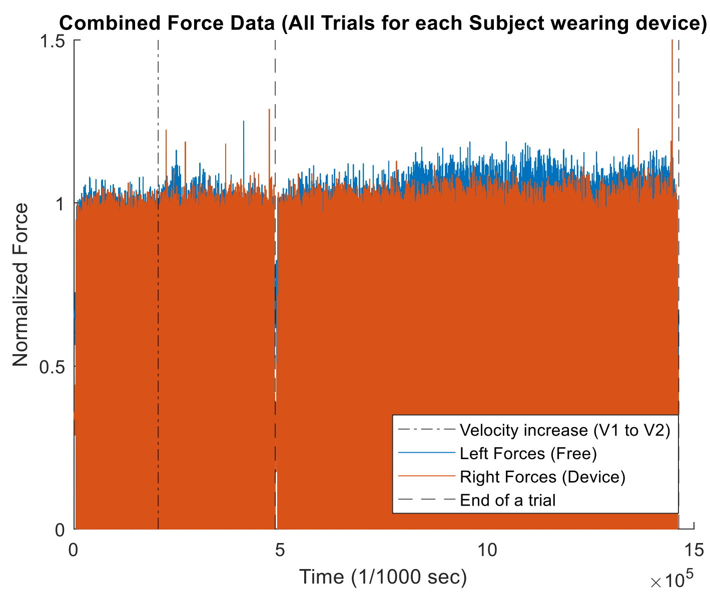

Figure 0.30: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 7, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

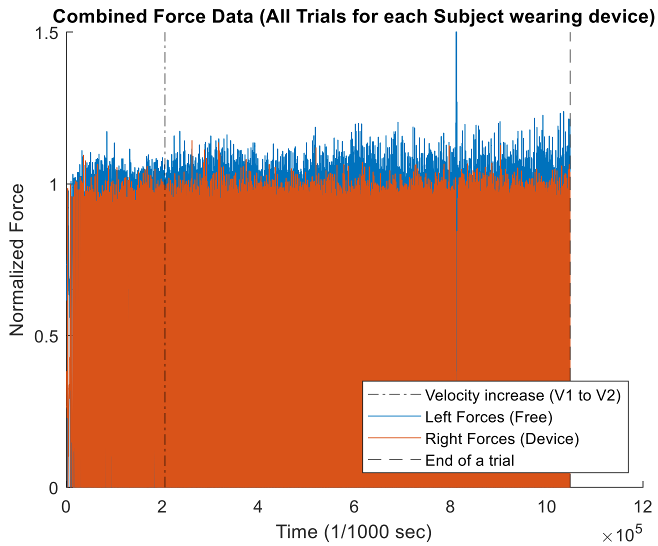

Figure 0.31: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 8, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).

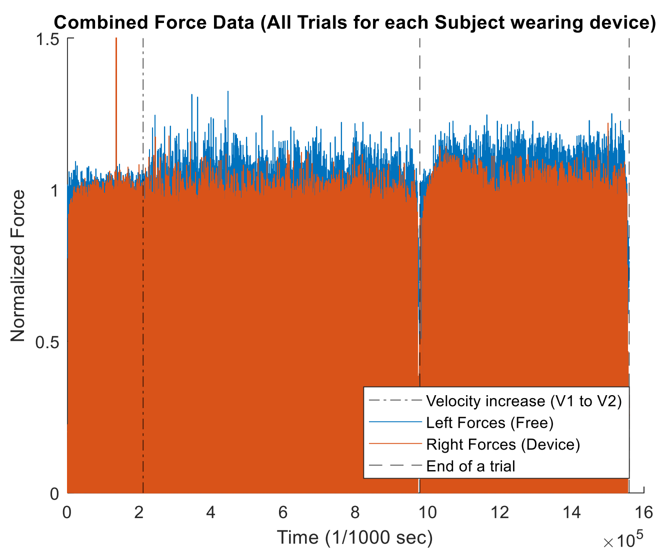

Figure 0.32: Normalized left (leg without the device) and right (leg with the device) forces by body weight, for subject 9, for all trials walking with the device. A dot-dash line indicating the change from velocity 1 to velocity 2 and a dash-dash line indicating an end of a walking trial (stop for a break and/or an adjustment of the device).